Early Reionization Science from 21 cm Experiments and the Path Towards a New Cosmological Probe

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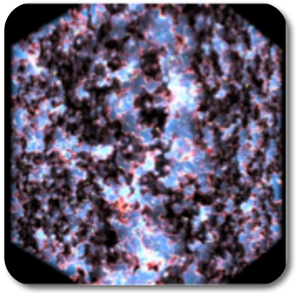
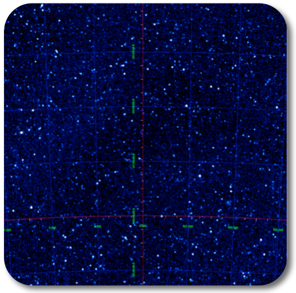
Brown University

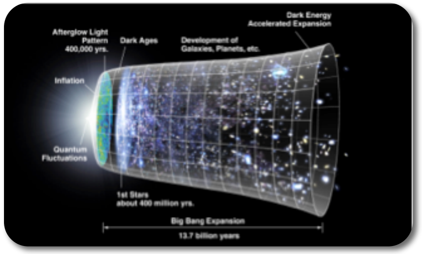
Fermilab AstroSeminar / Tianlai Workshop
September 26, 2016

Photo Credit: Peter Wheeler, ICRAR

Outline

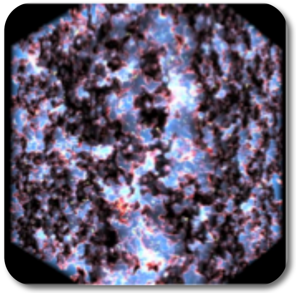






21 cm Signal (Background) | Other Emission (Foregrounds) | Instrument | Science

Outline



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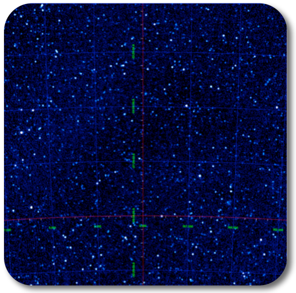

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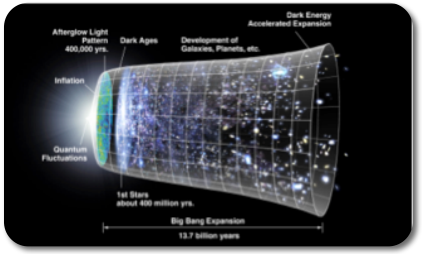
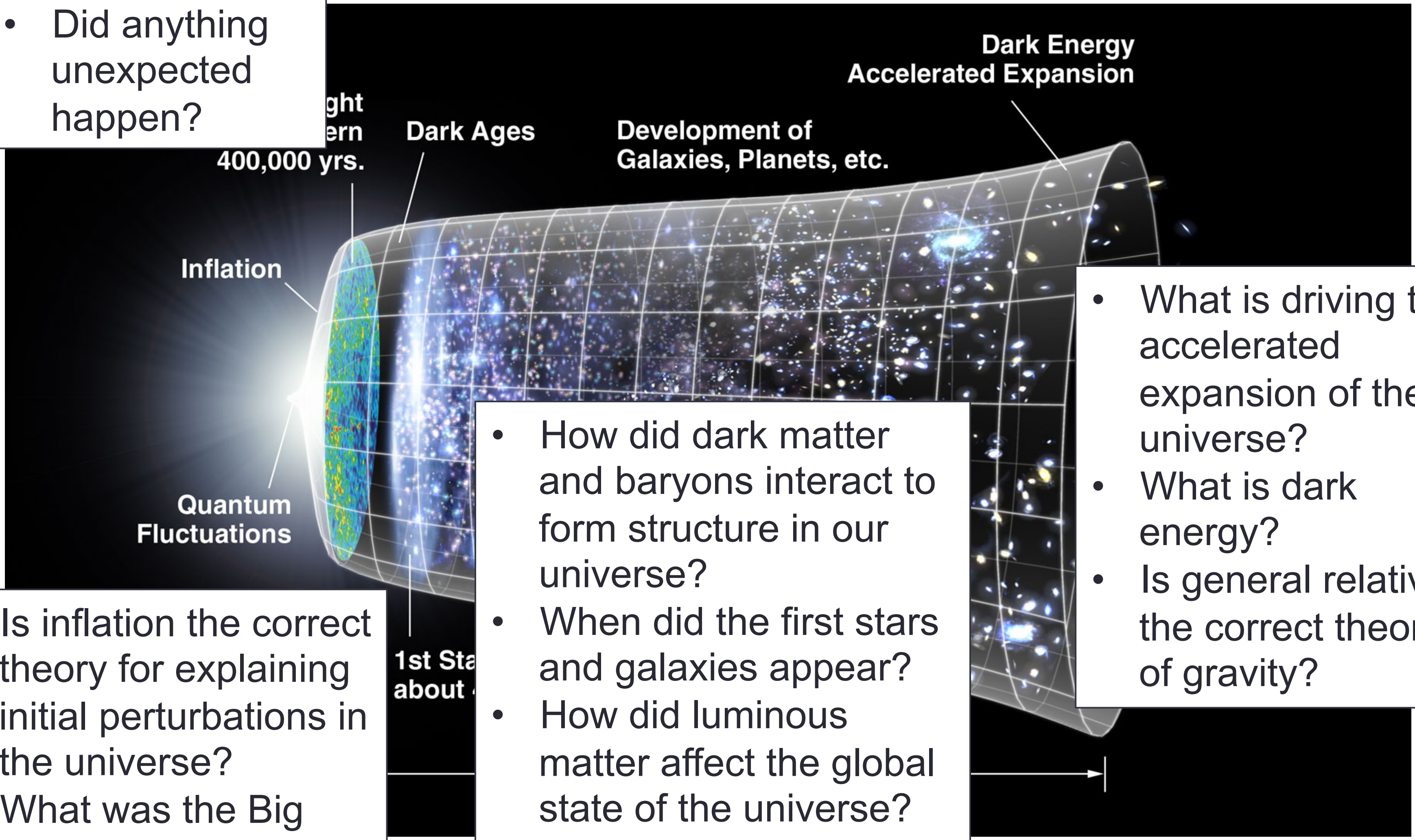


Science

Science Drivers

- Did anything unexpected happen?



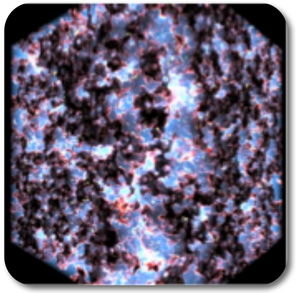
- What is driving the accelerated expansion of the universe?
- What is dark energy?
- Is general relativity the correct theory of gravity?

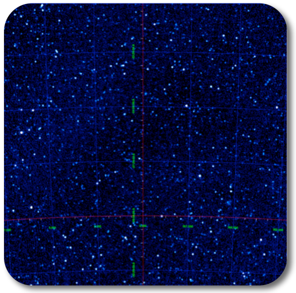
- How did dark matter and baryons interact to form structure in our universe?
- When did the first stars and galaxies appear?
- How did luminous matter affect the global state of the universe?

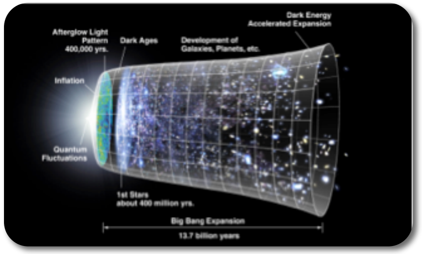
- Is inflation the correct theory for explaining initial perturbations in the universe?
- What was the Big Bang?

Credit: NASA/WMAP Science Team

Outline







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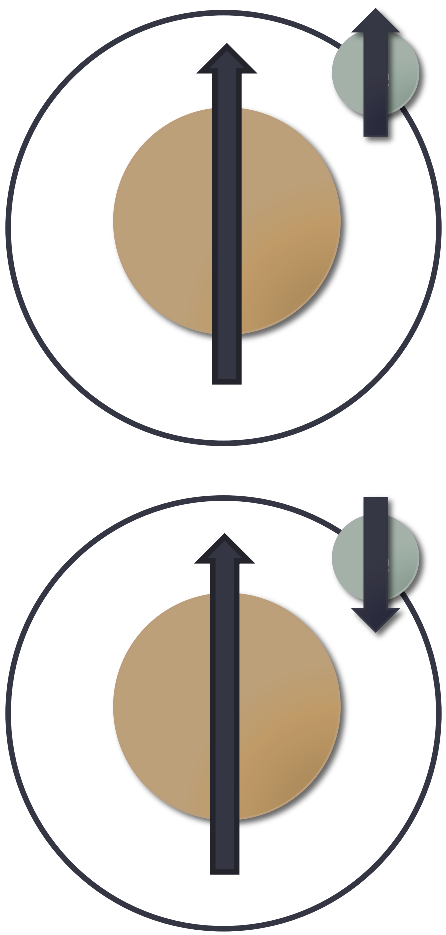
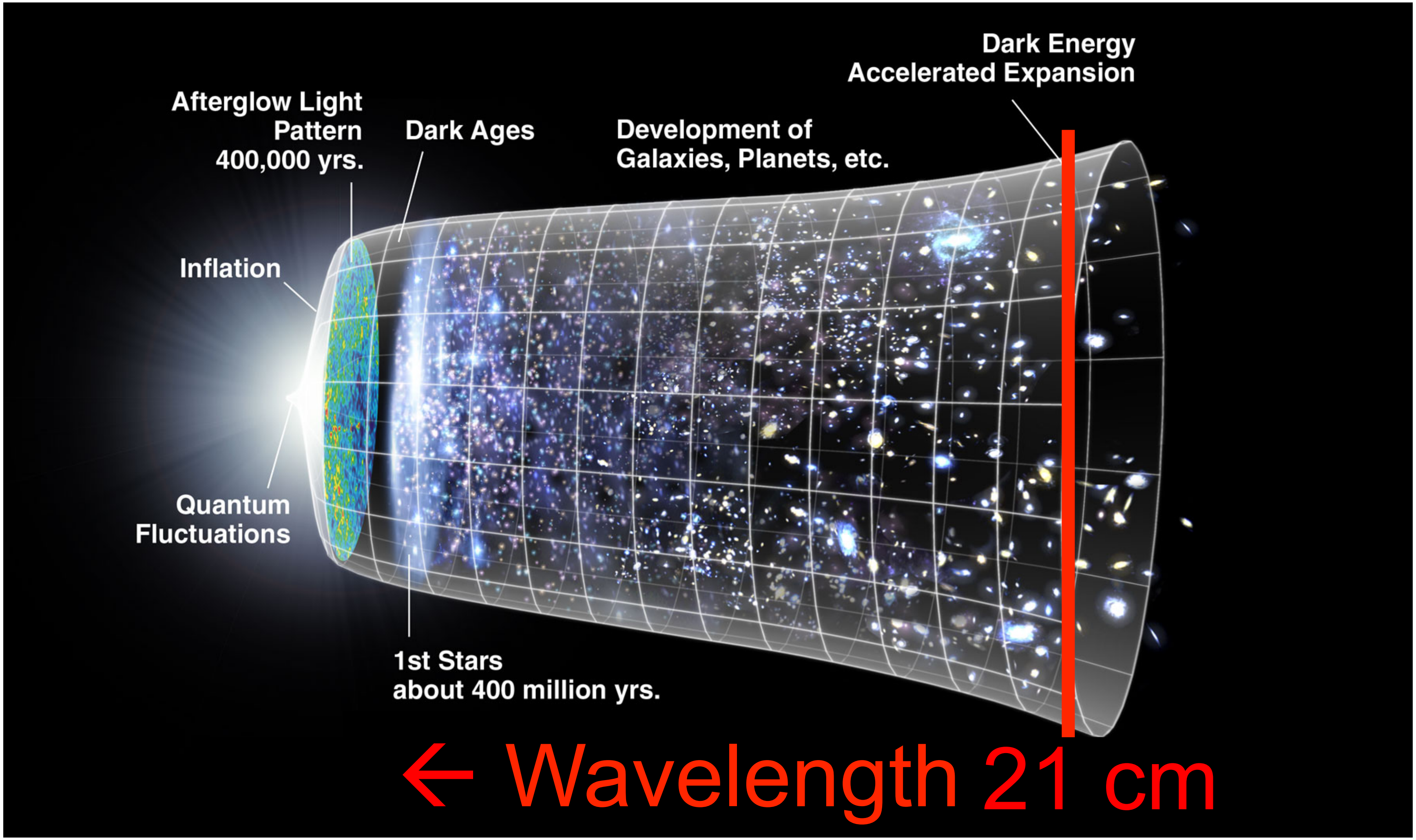
Science

21 cm = Hydrogen



- The most abundant element in the universe
  - 75% of all baryons by mass
- Hyperfine splitting energy differential of 5.9×10^{-6} eV
  - ν = 1420 MHz
  - λ = 21 cm
  - T = 0.068 K

21 cm Cosmology



Credit: NASA/WMAP Science Team

21 cm Cosmology

- Observing at different wavelengths/frequencies probes different epochs of cosmic history
  1. Dark Ages (15 Myr – 180 Myr, z = 100 – 20, ν_{21cm} = 15 – 70 MHz)
  2. Epoch of Reionization (180 Myr – 1 Gyr, z = 20 – 5, ν_{21cm} = 70 – 240 MHz)
  3. Post-reionization (1 Gyr – present, z = 5 – 0, ν_{21cm} = 240 – 1420 MHz)

- Potential to provide 3D map of the universe through the lens of neutral hydrogen

Credit: Scientific American, DARE Collaboration

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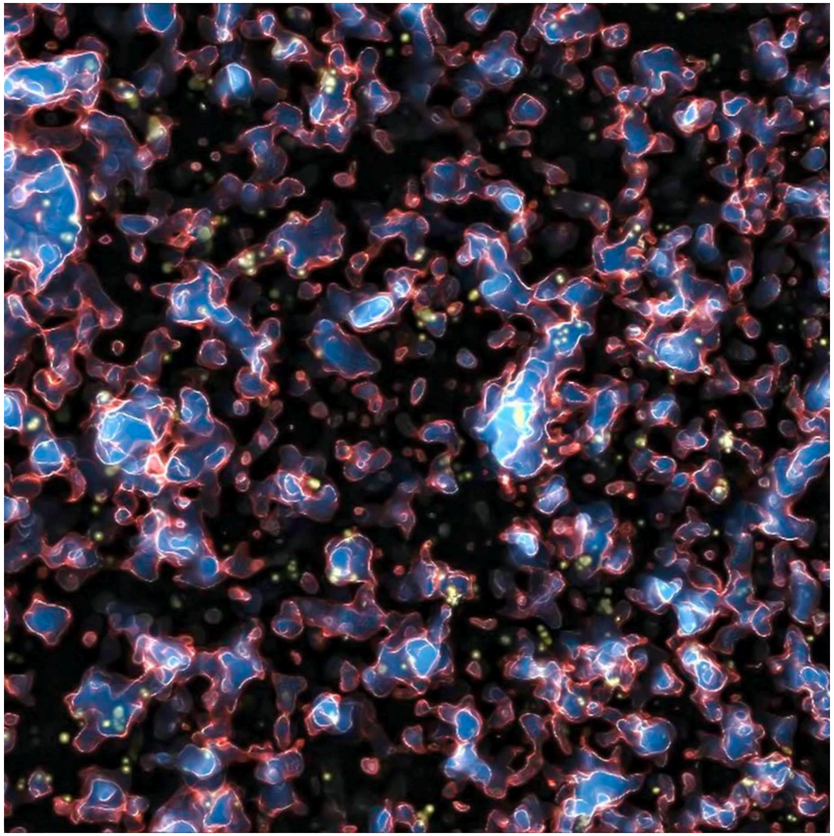
The Epoch of Reionization (EoR)

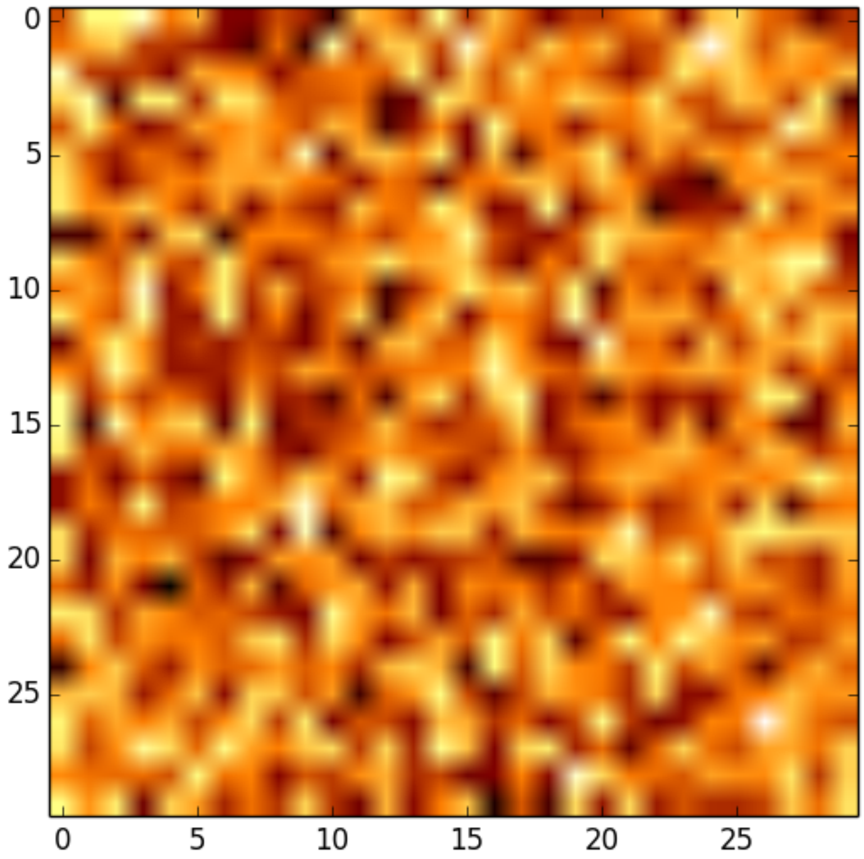
Imaging the EoR

Real Space



Imaging the EoR

Real Space



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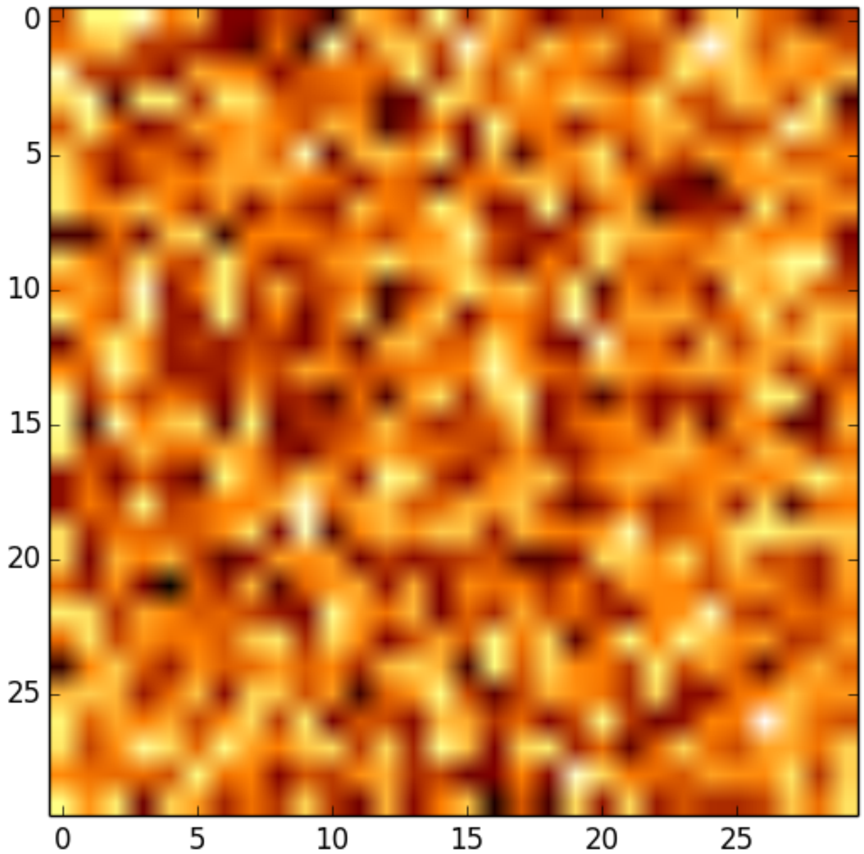
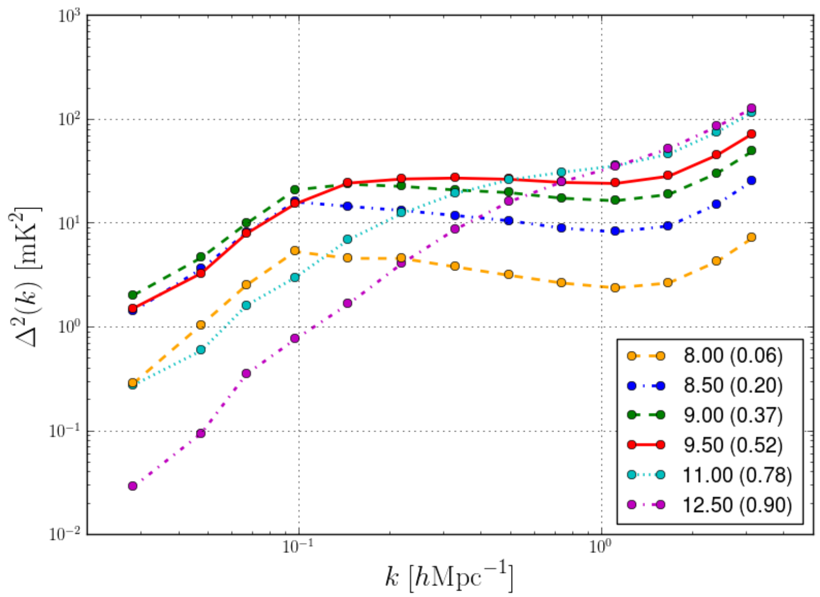


Power Spectrum



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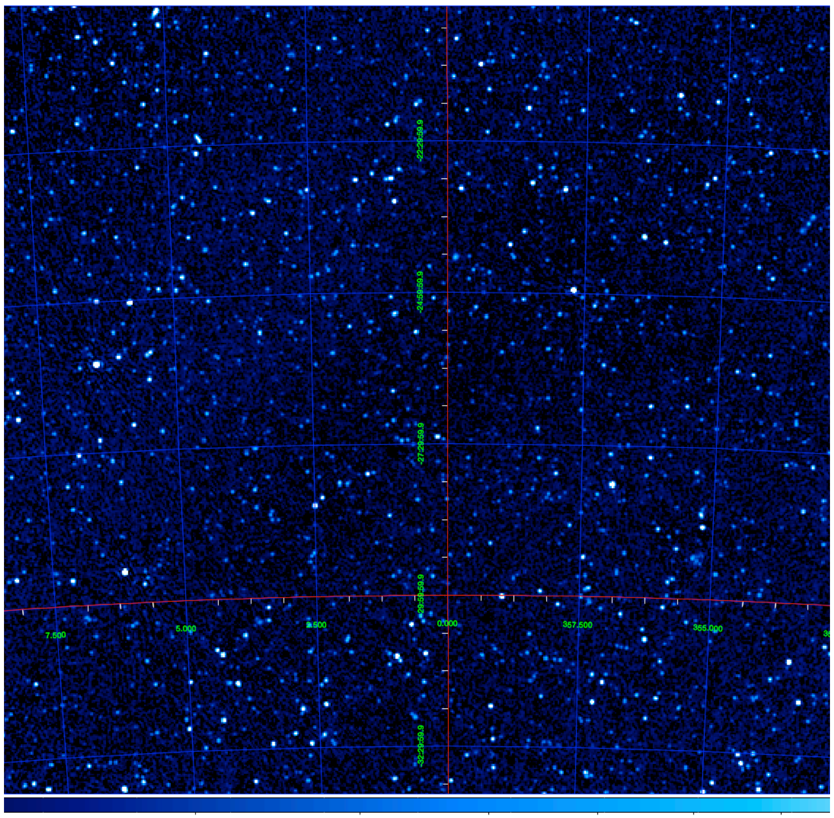

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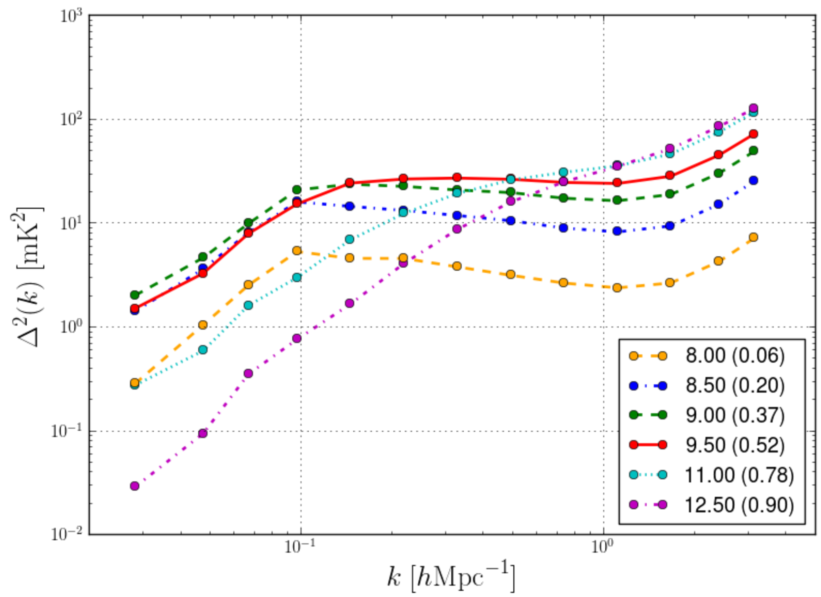
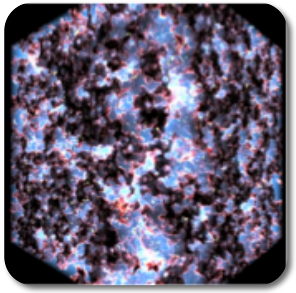
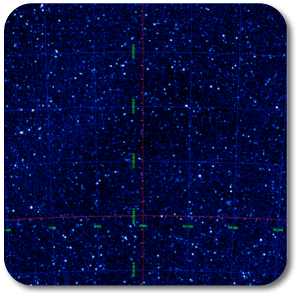
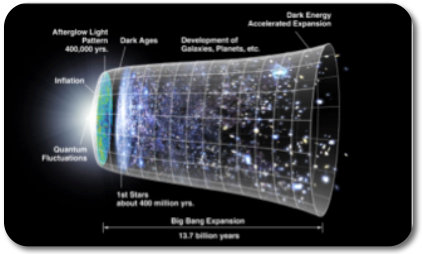


Outline







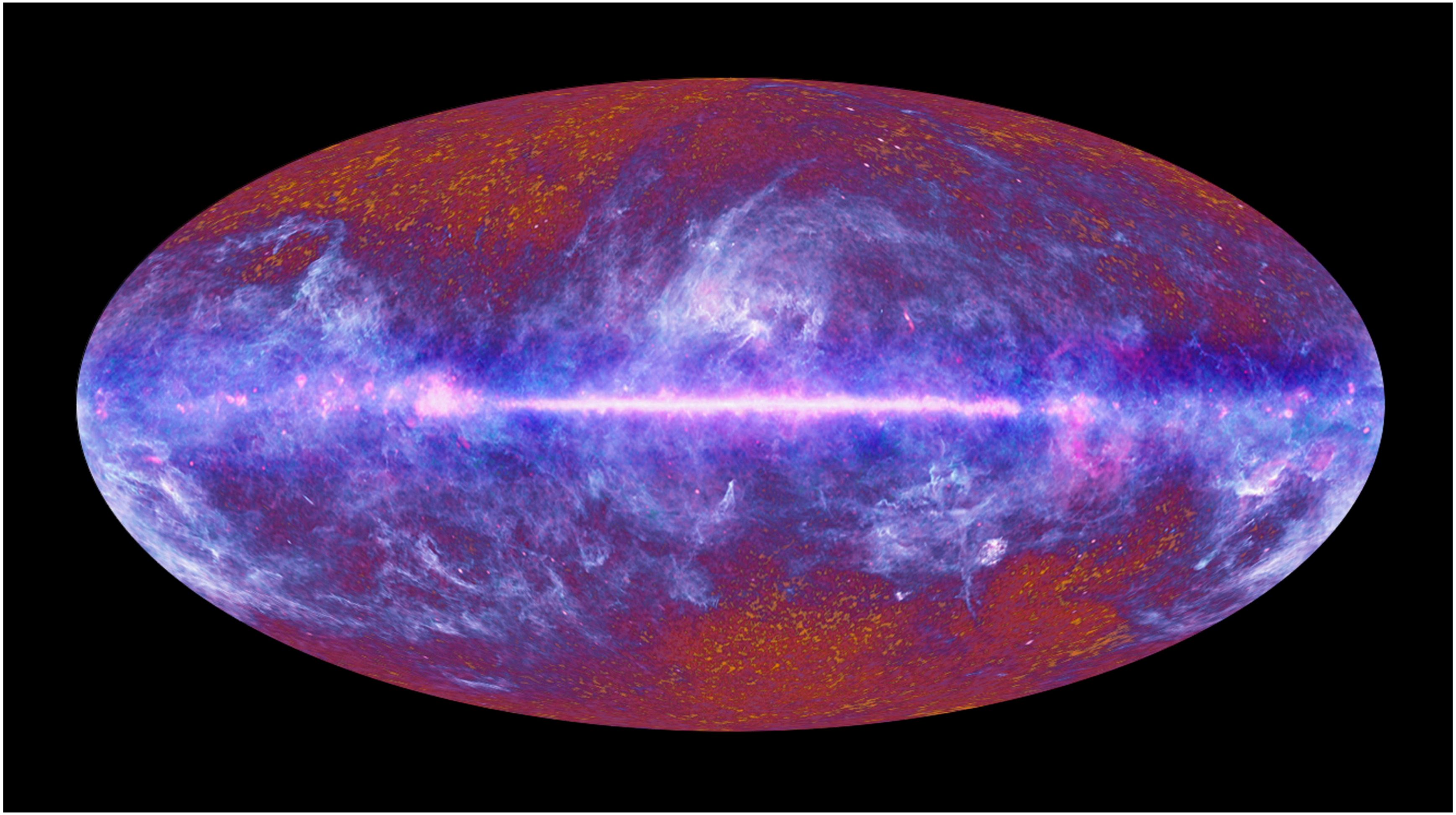
21 cm Signal (Background)

Other Emission (Foregrounds)

Instrument

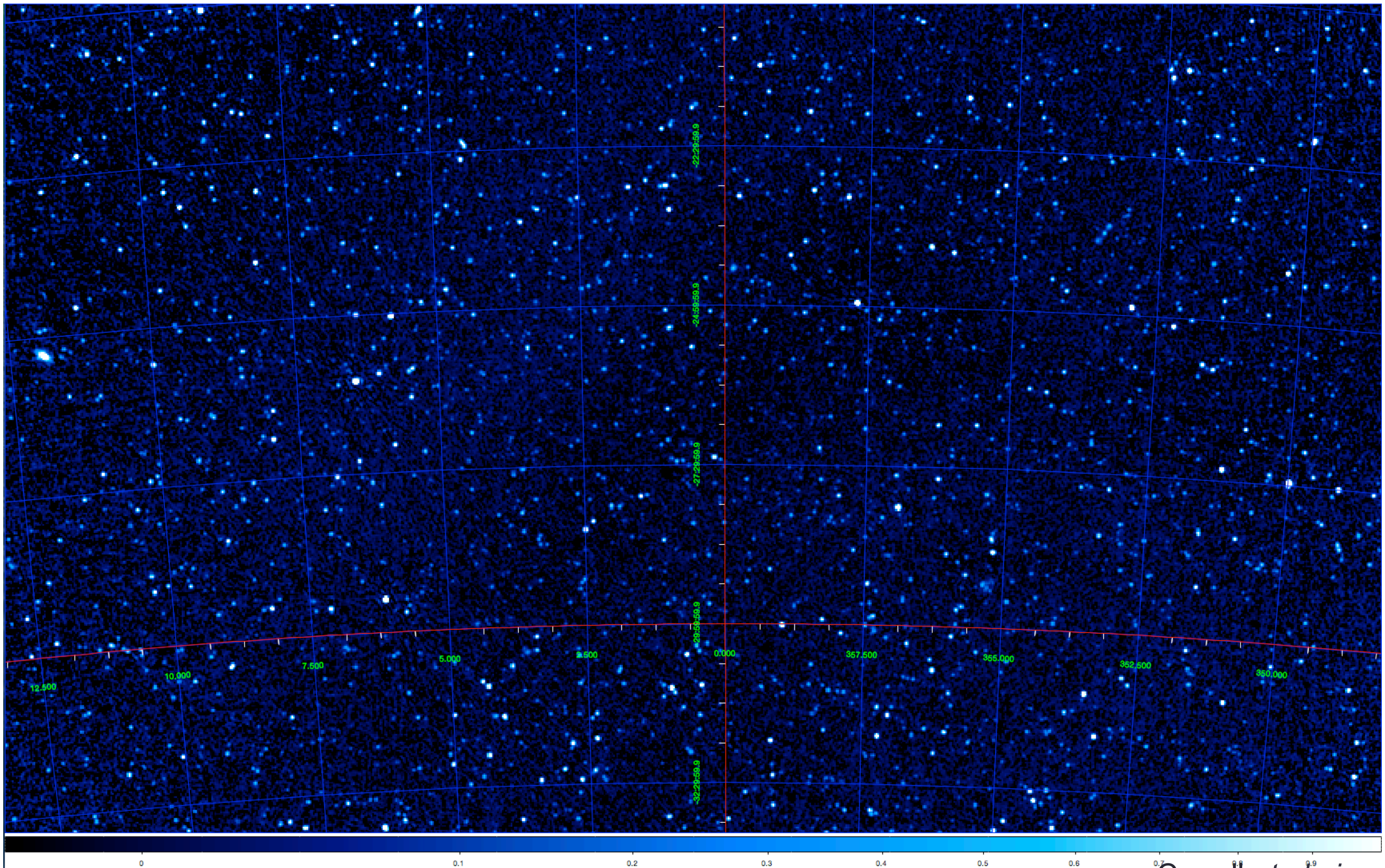
Science

Foregrounds – Nothing New!



Credit: Planck Collaboration

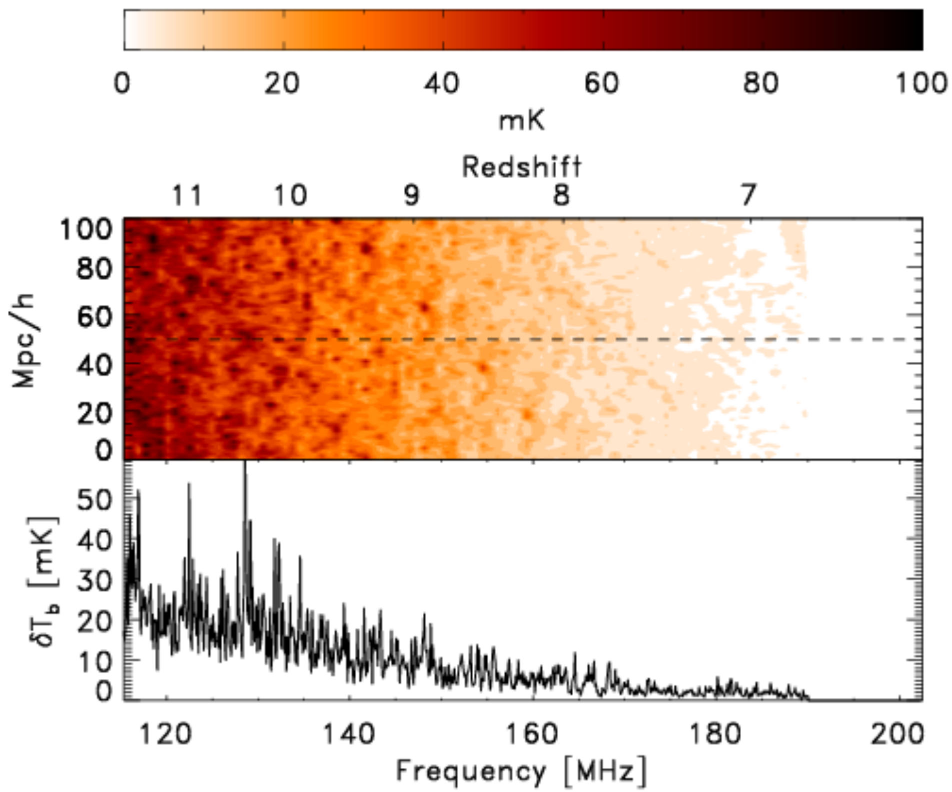
Foregrounds – From Bad to Worse



Carroll *et al.*, *in prep.*

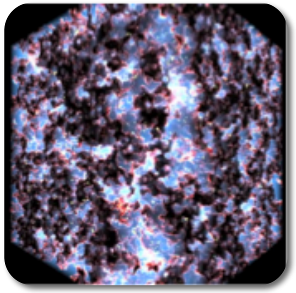
21 cm Foregrounds

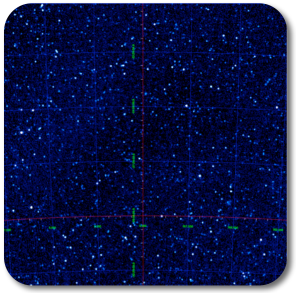
- Foreground emission swamps 21 cm signal by 4 – 5 orders of magnitude
- Foreground emission mechanisms are *power-law* synchrotron and bremsstrahlung
- 21 cm signal varies rapidly with frequency
- Separate from 21cm signal using ***spectral smoothness***

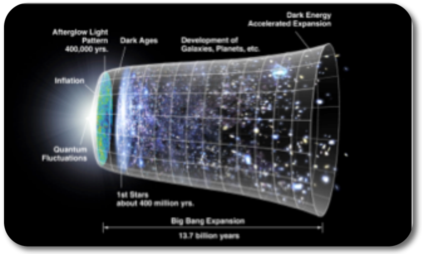


Jelic *et al.* 2008

Outline







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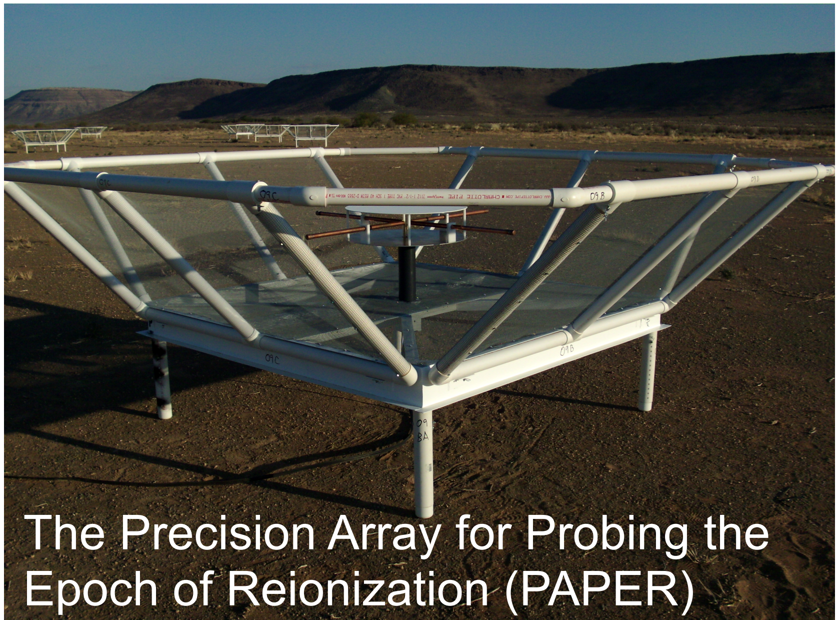
21 cm Experiments



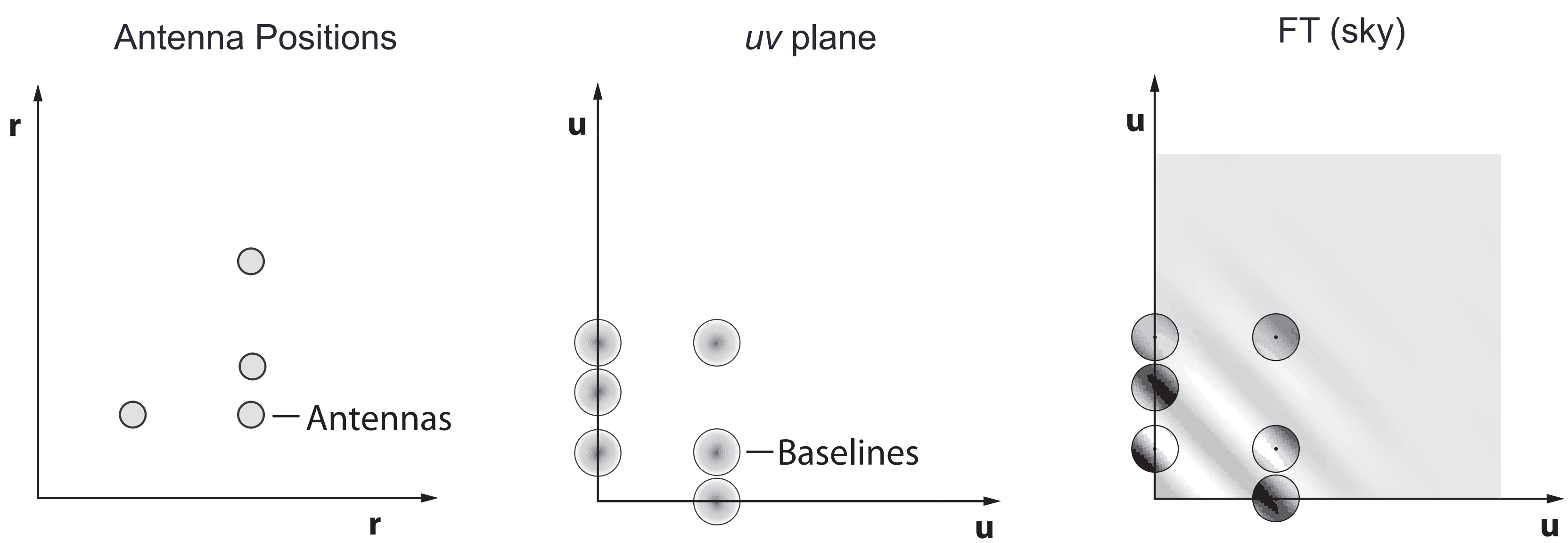
The Precision Array for Probing the Epoch of Reionization (PAPER)

The Murchison Widefield Array (MWA)

- Dynamic range between signal and foregrounds represents a new challenge for interferometry
- ***Make sure your instrument doesn't make foregrounds look "unsmooth"***
- Requires stability and calibratability
- Answer: dedicated instruments with simple elements

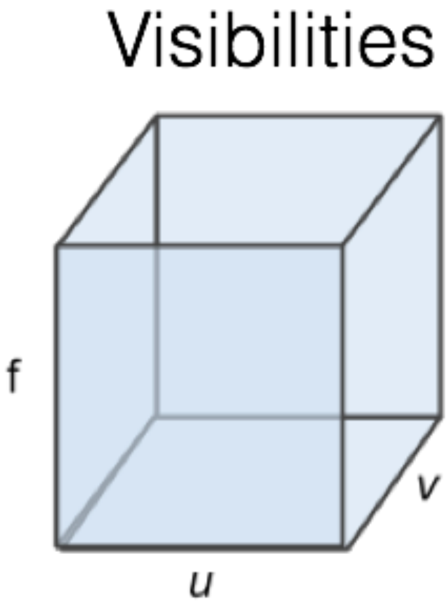
Interferometers

- Each *baseline* measures one Fourier mode of the sky (*visibility*)
- Want many unique baselines to reconstruct images

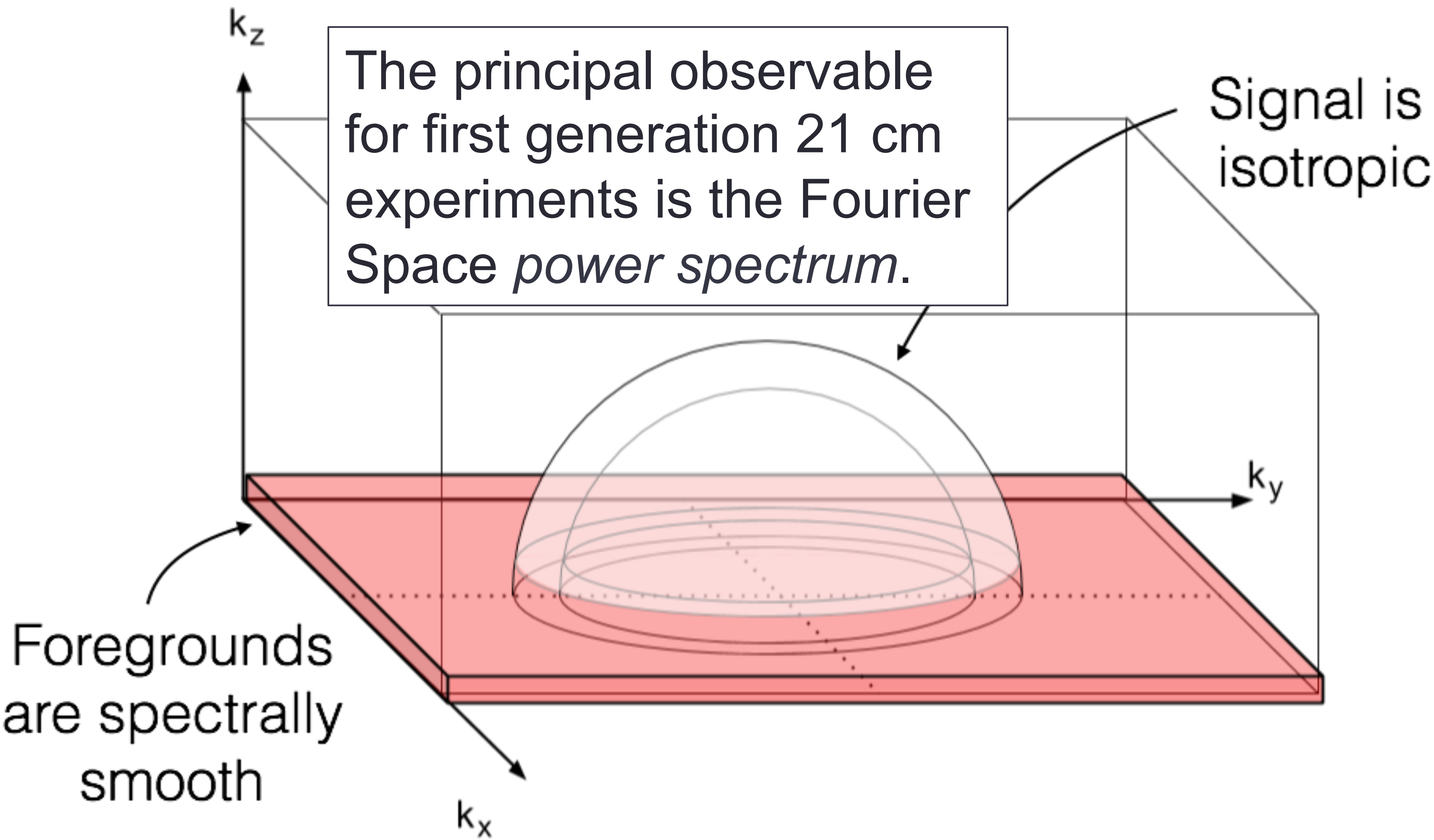


Morales & Wyithe 2010

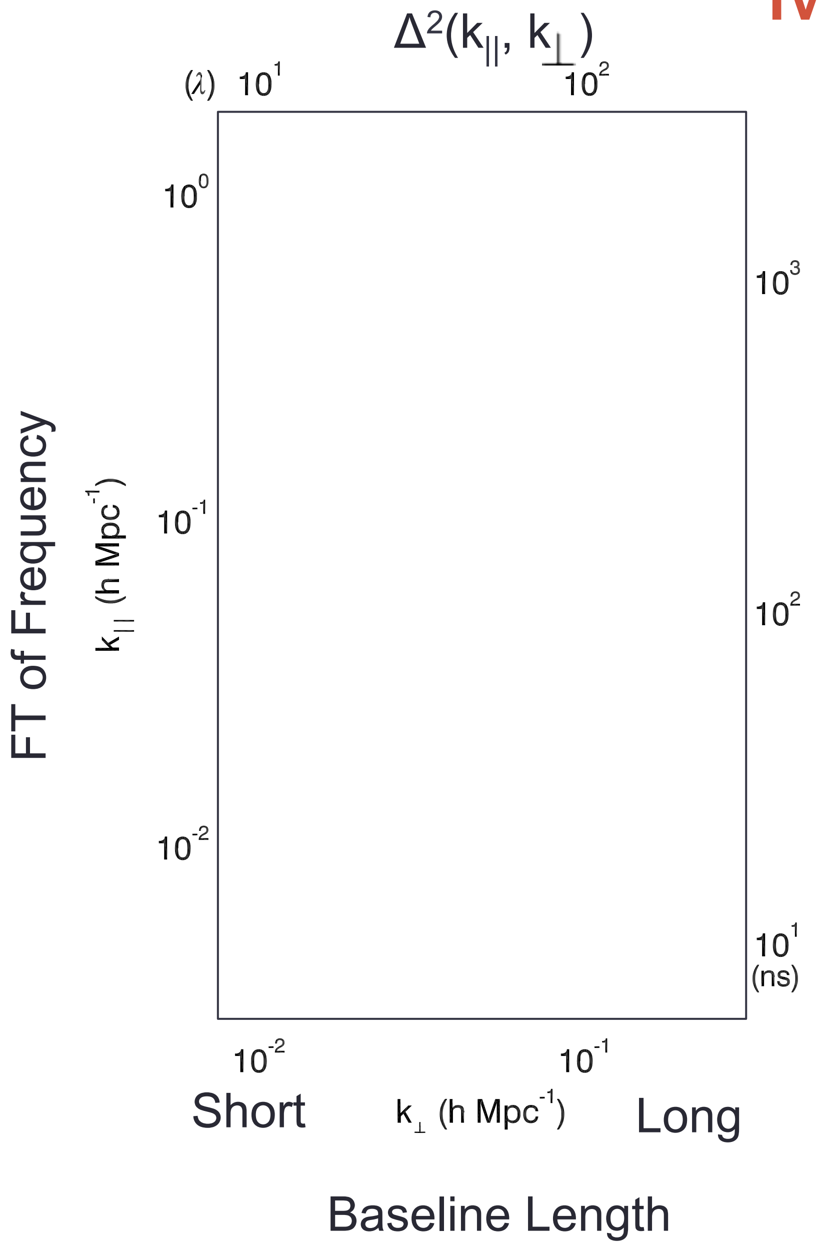
Cosmological Fourier Space



The Power of Fourier Space



Mode Mixing & The Wedge



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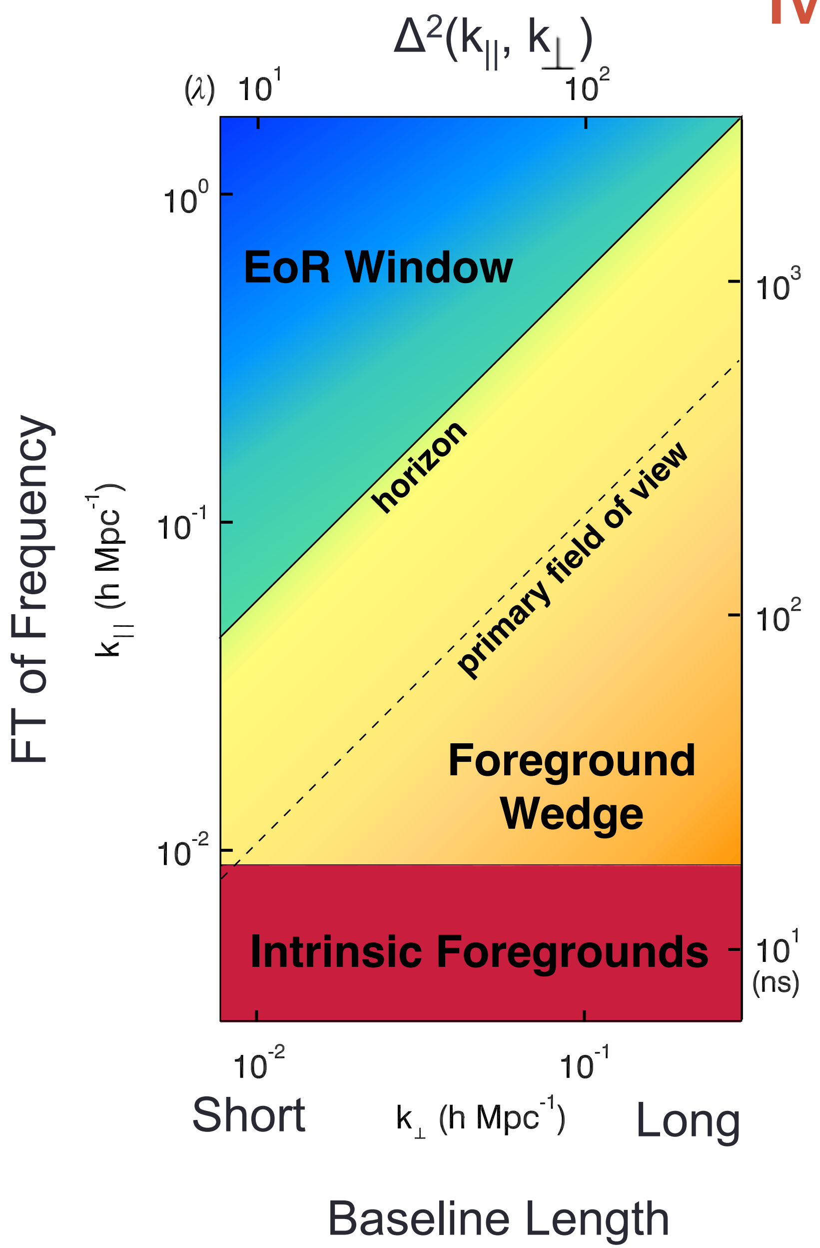

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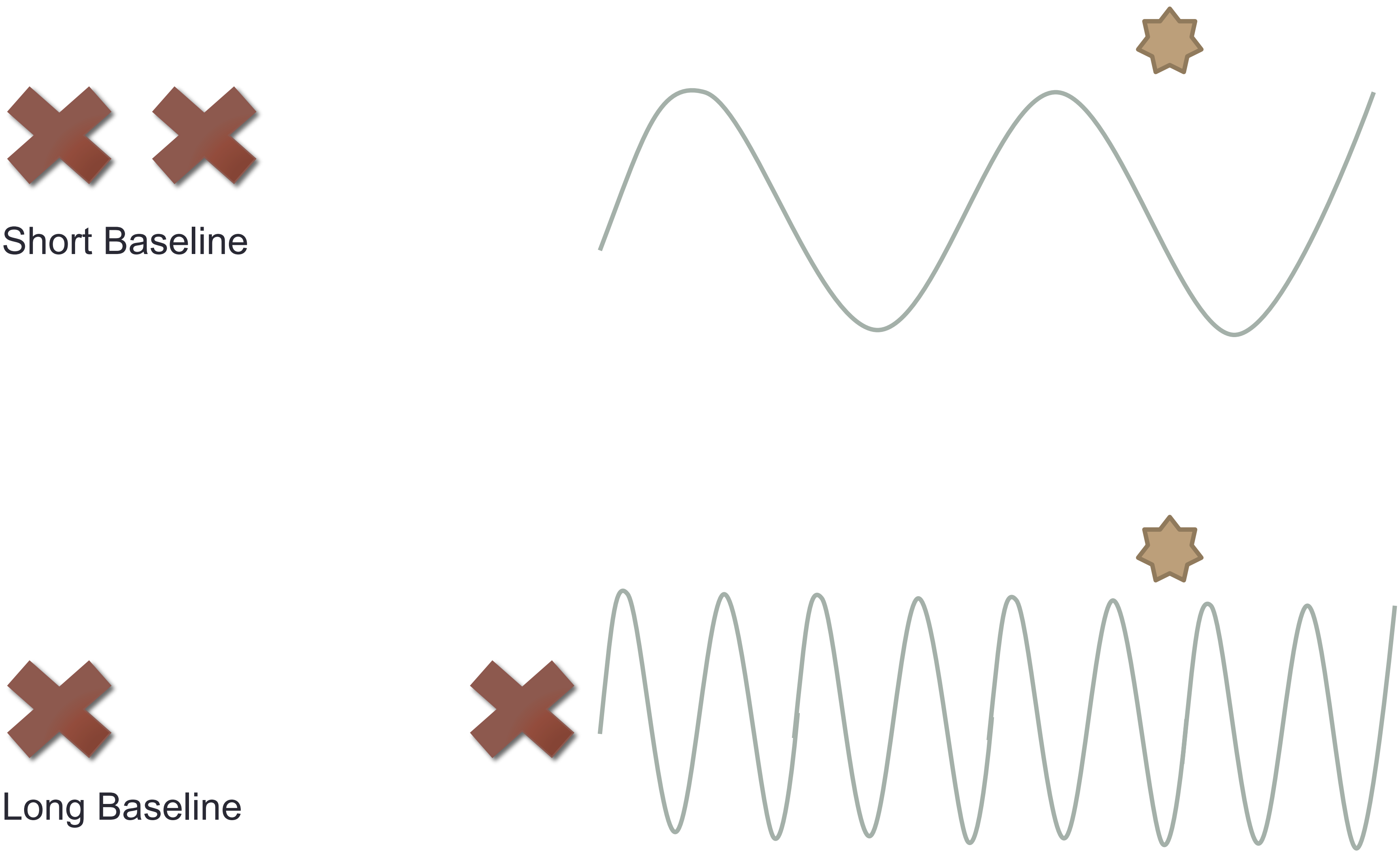

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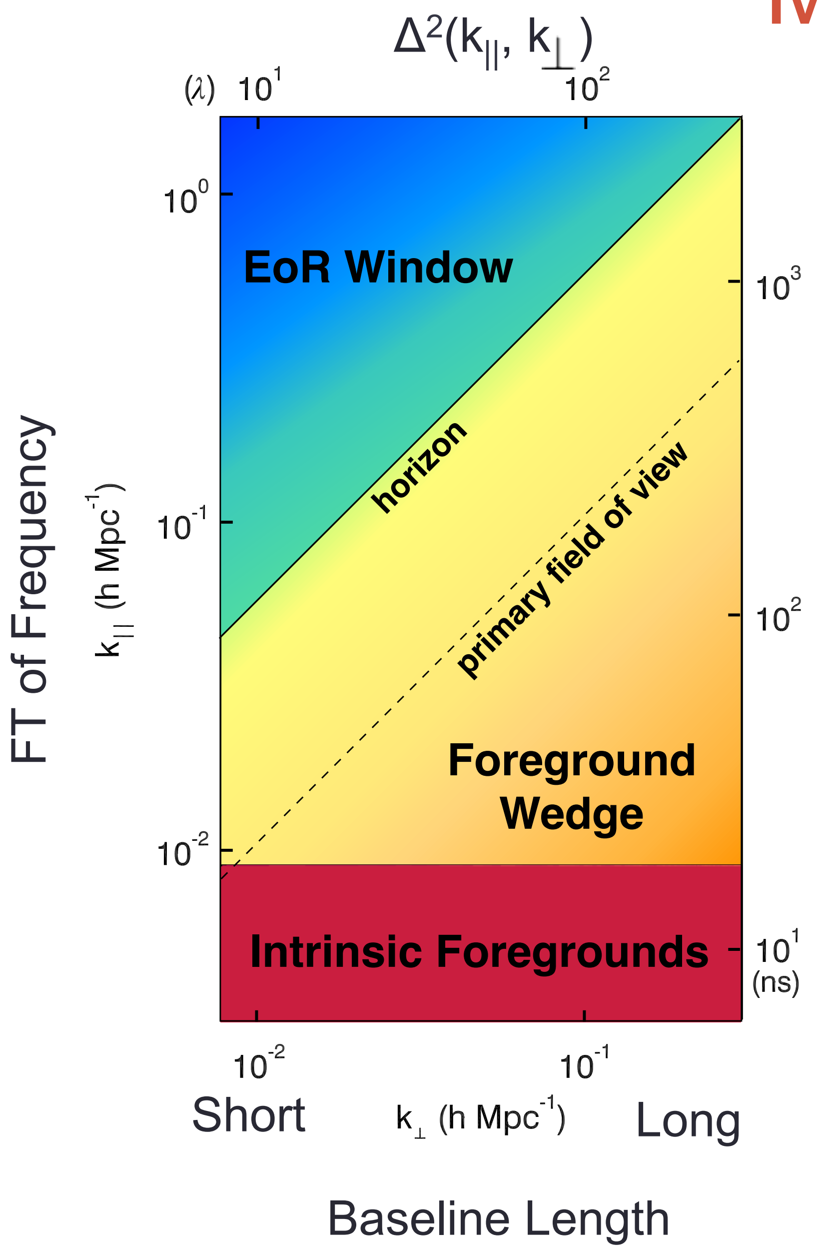

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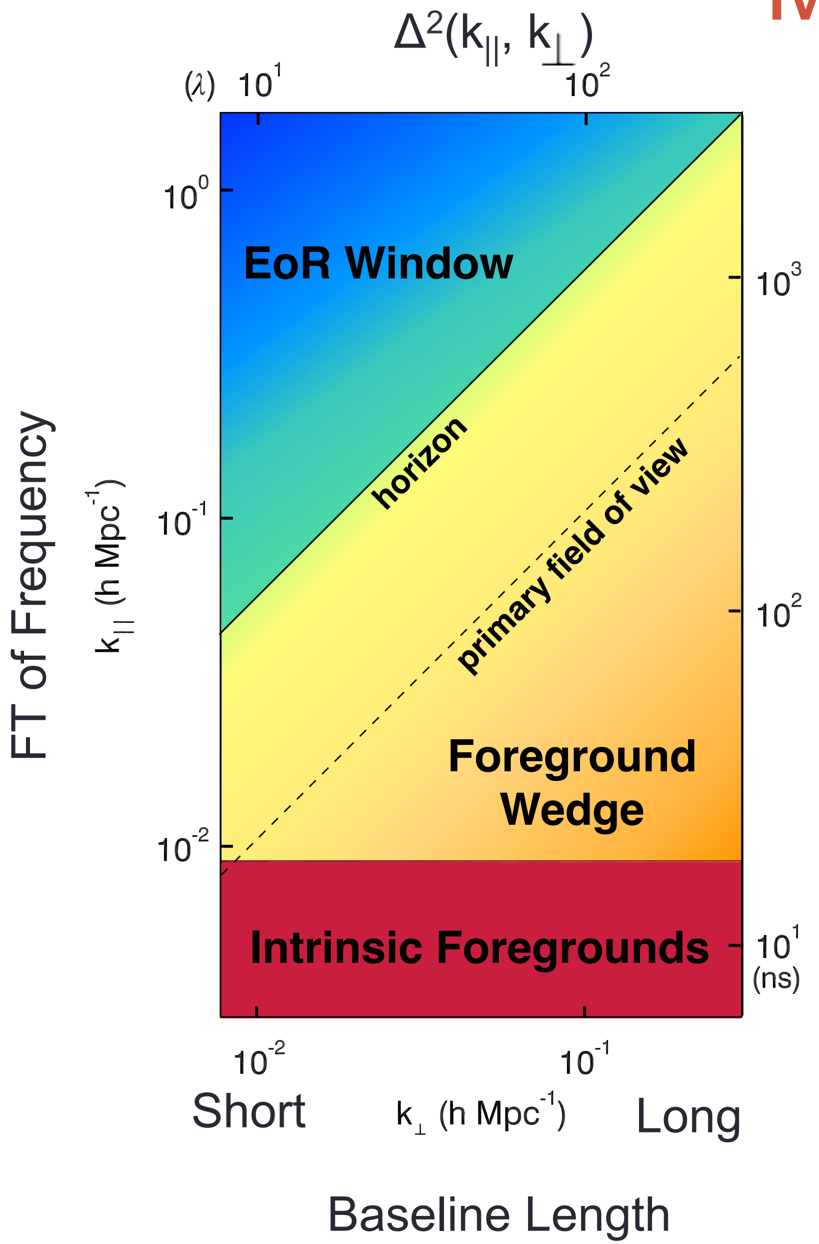

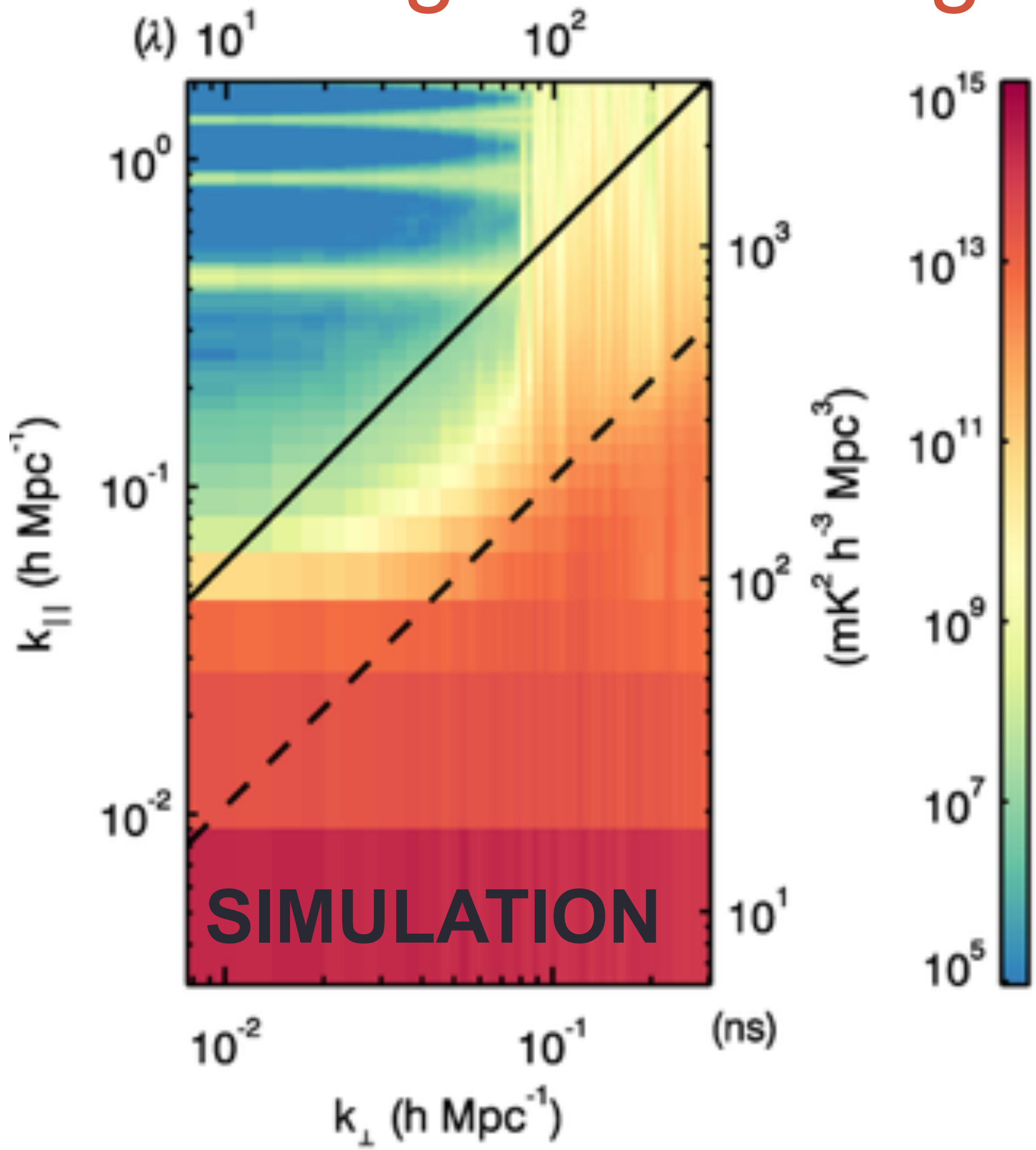

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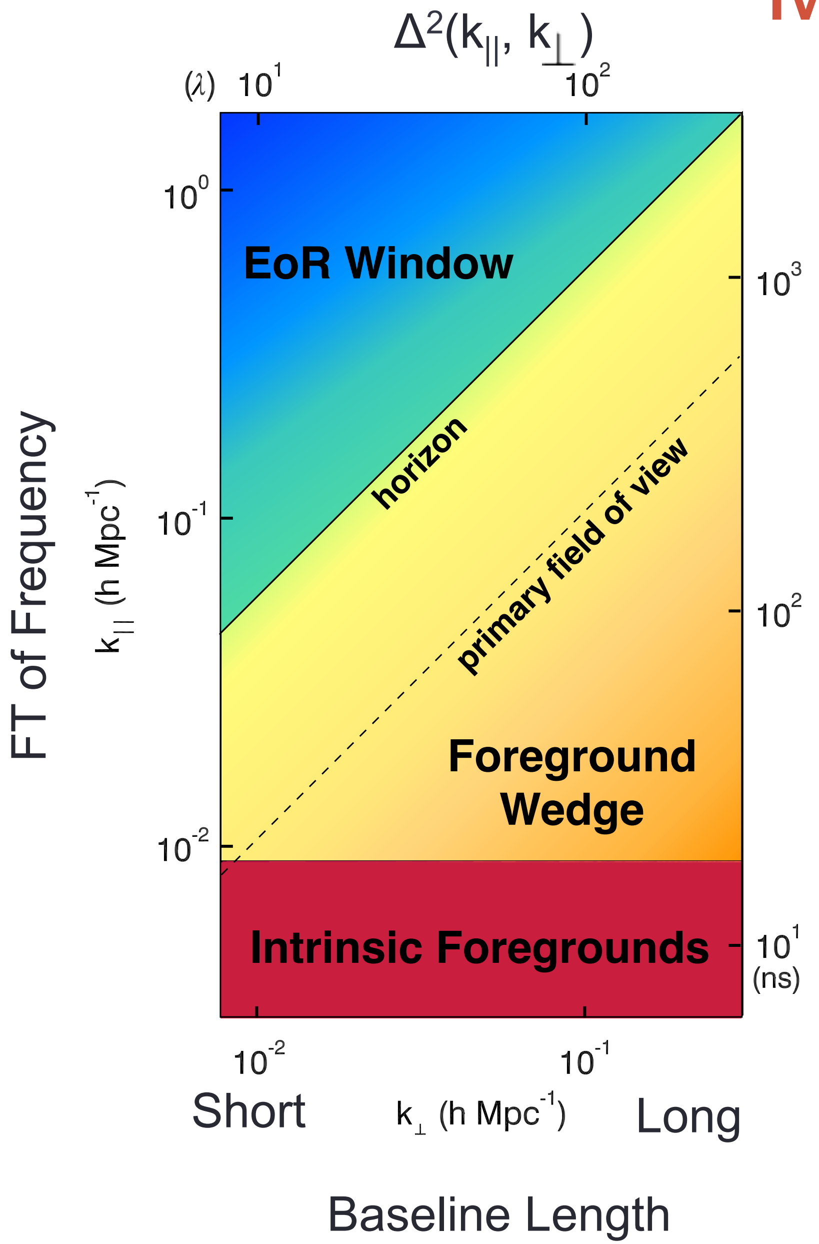

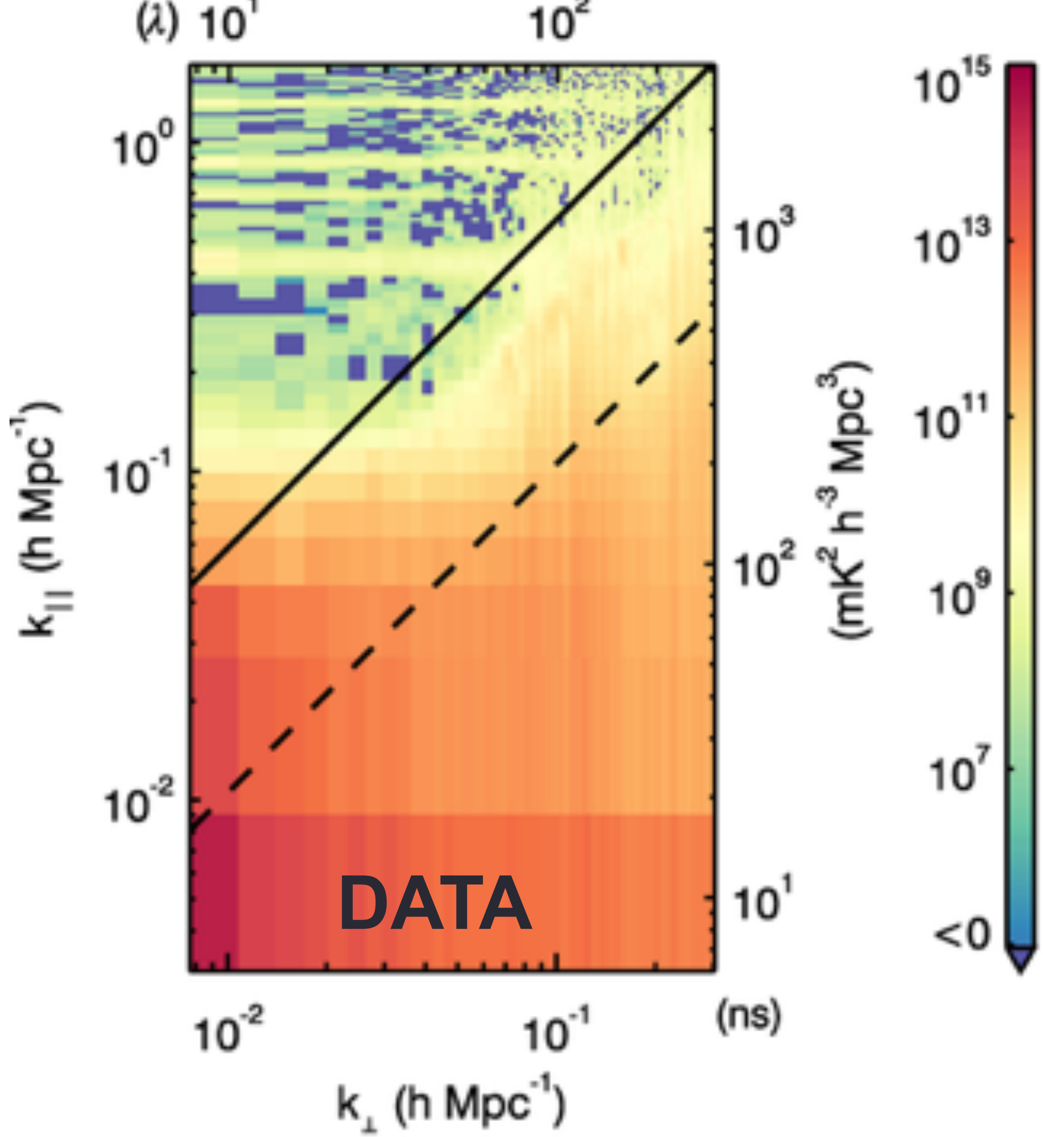

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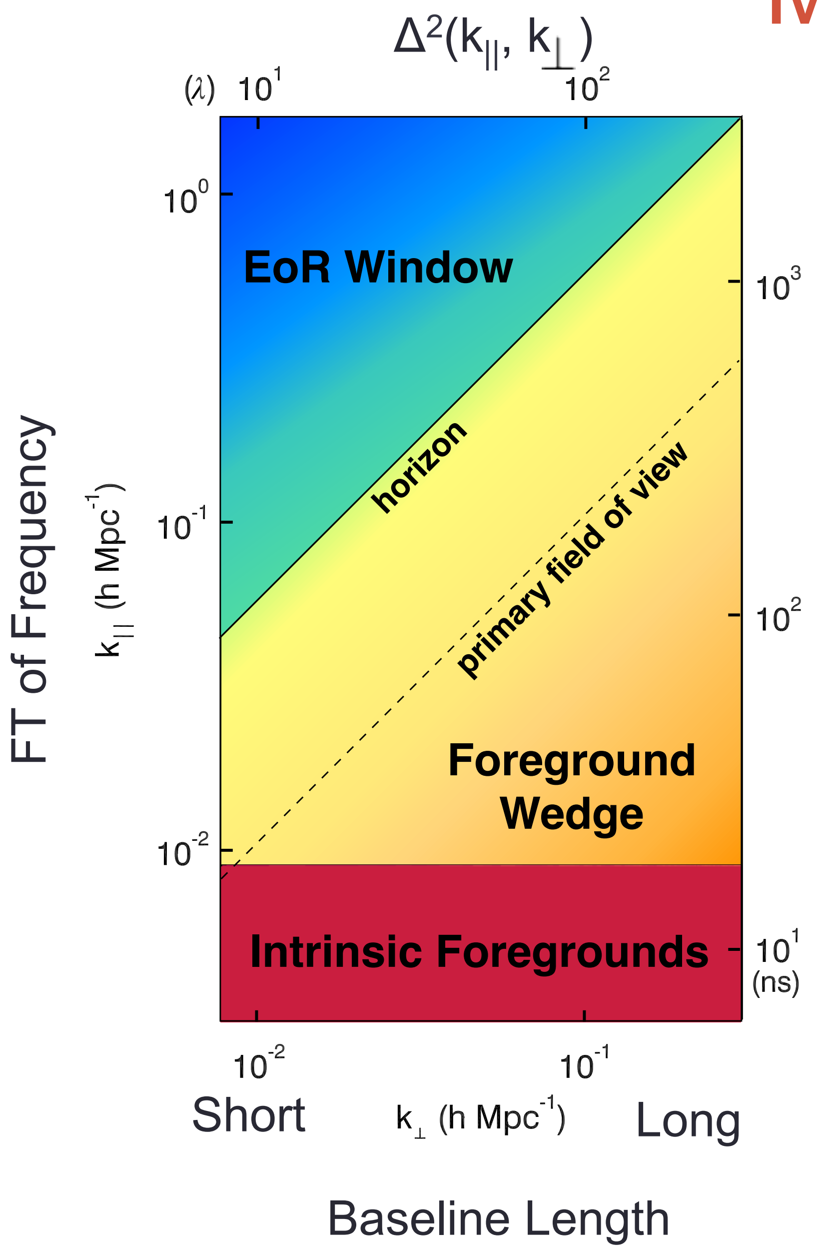


Two principal analysis goals:

1. Keep the window **clean** (“Foreground avoidance”)
2. Make the window **bigger** (“Foreground subtraction”)

The Wedge Paradigm at Other Redshifts

- Wedge slope is a function of *redshift*:

$$k_{\|,\mathrm{hor}} = \frac{2\pi}{Y}\frac{|\boldsymbol{b}|}{c} = \left(\frac{1}{\nu}\frac{X}{Y}\right)k_{\perp}$$

  - X converts from radians (primary beam) to Mpc
  - Y converts from Hz (bandwidth) to Mpc
  - Depend on on angular diameter distance, Hubble constant

- Wedge slope is 3.7 at z = 9.5, but only 0.8 at z = 1.2!
  - Lose many fewer modes to the wedge

Aside: Noise

- X & Y also enter into the normalization of noise (measured in MHz/str) to cosmological Fourier space

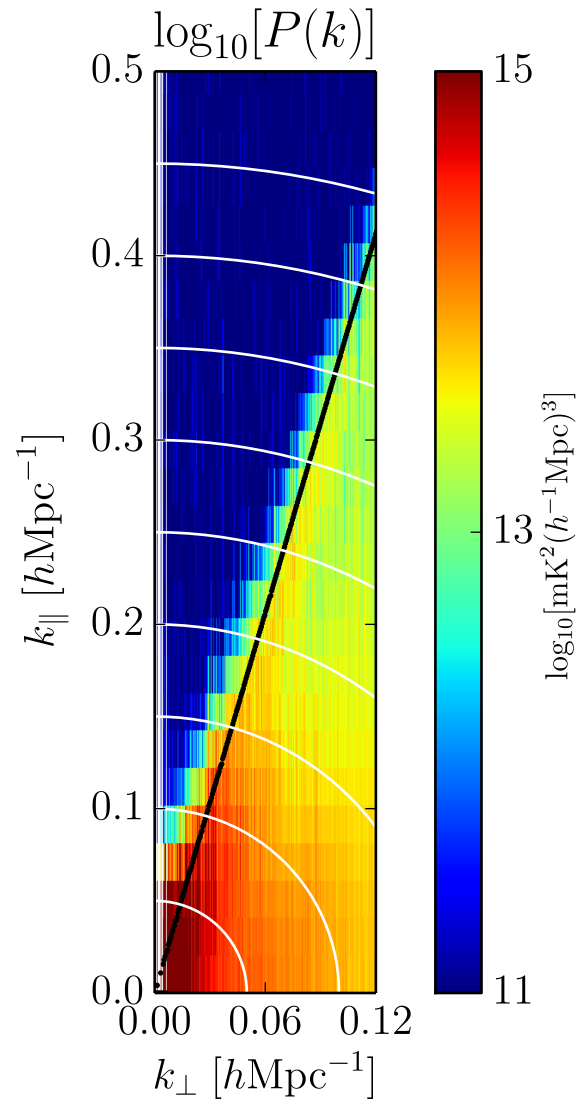
$$\Delta^2_{\mathrm{N}}(k) \approx X^2 Y \frac{k^3}{2\pi^2} \frac{\Omega}{2t} T^2_{\mathrm{sys}}$$

- X^2Y is 540 (h^{-1}Mpc)^3 at z = 9, but only 28 (h^{-1}Mpc)^3 at z = 1
  - Can be a significant reduction in noise for a low *z* experiment!

Pober *et al* 2013b

The Wedge (To Scale)

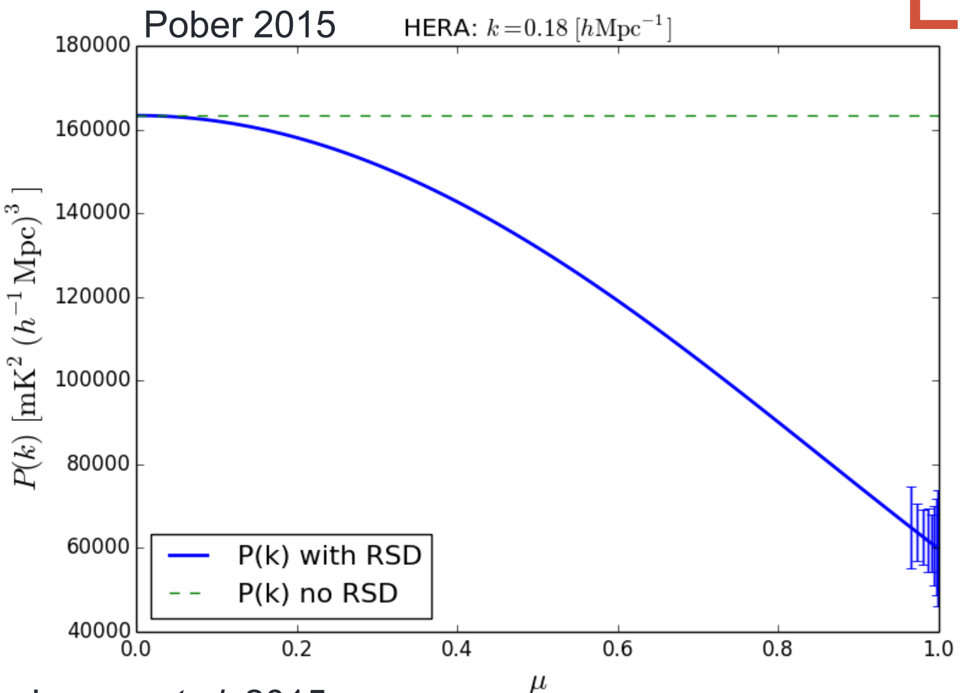
- EoR instruments do not probe $k_{||}$ and $k_{\perp}$ on equal scales
  - 100 kHz resolution ➔ $k_{||,max}$ ~ 5 h/Mpc
  - 300 m baseline ➔ $k_{\perp,max}$ ~ 0.15 h/Mpc
- 21 cm EoR experiments probe line of sight k modes
- Scales are much better matched at low z



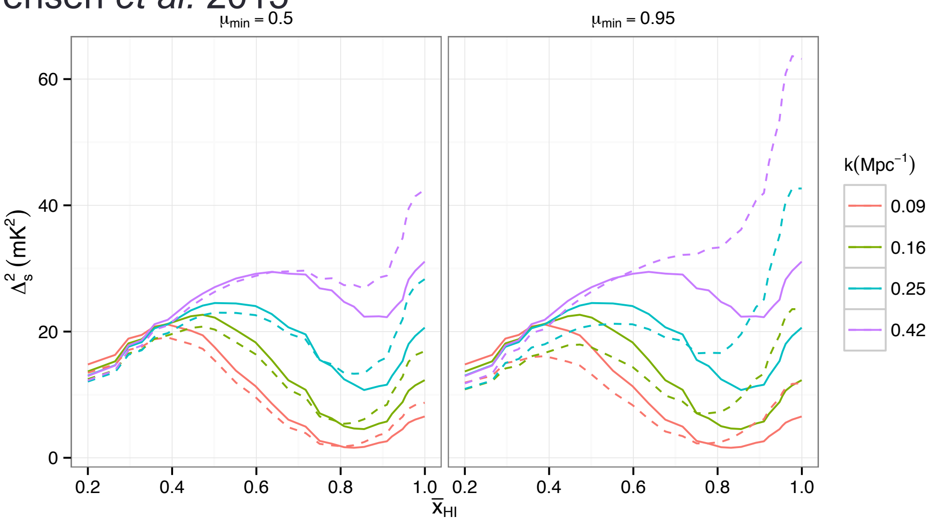
Pober 2015

Line of Sight Modes

Pober 2015

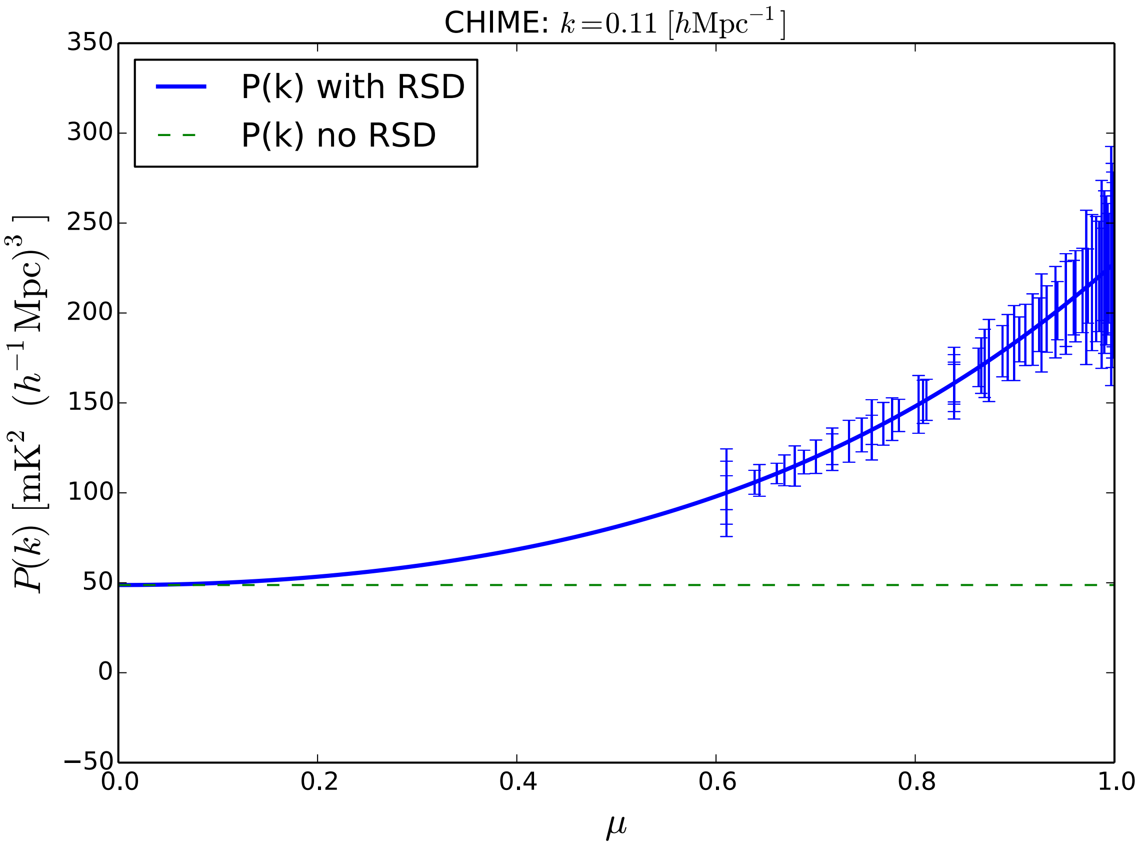


Jensen *et al.* 2015



- Observed power spectrum is in *redshift space* – not isotropic
- Anti-correlation between density and ionization fields can *decrease* line of sight power during EoR
- Potential for "wedge" bias if not accounted for (Jensen *et al.* 2015)

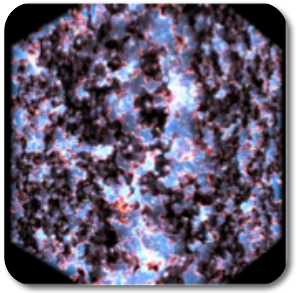
Line of Sight Modes

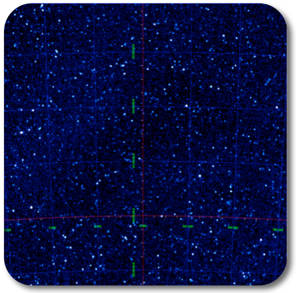


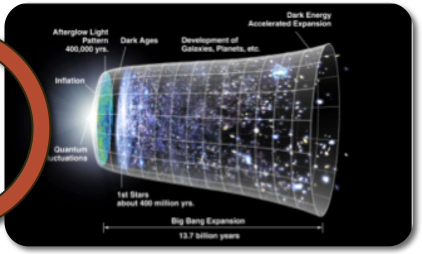
Pober 2015

- Significantly shallower wedge slope for low *z* alleviates the issue
- Foreground avoidance can be an especially powerful technique for low *z* 21 cm experiments!

Outline







21 cm Signal
(Background)

Other Emission
(Foregrounds)

Instrument

Science

Two Critical Paths Forward

- Making the most out of first generation experiments
  - More rigorous testing (data simulation, multiple pipelines)
  - Continued analysis (and cross-analysis) of existing data sets
- Building on lessons learned for a second generation experiment

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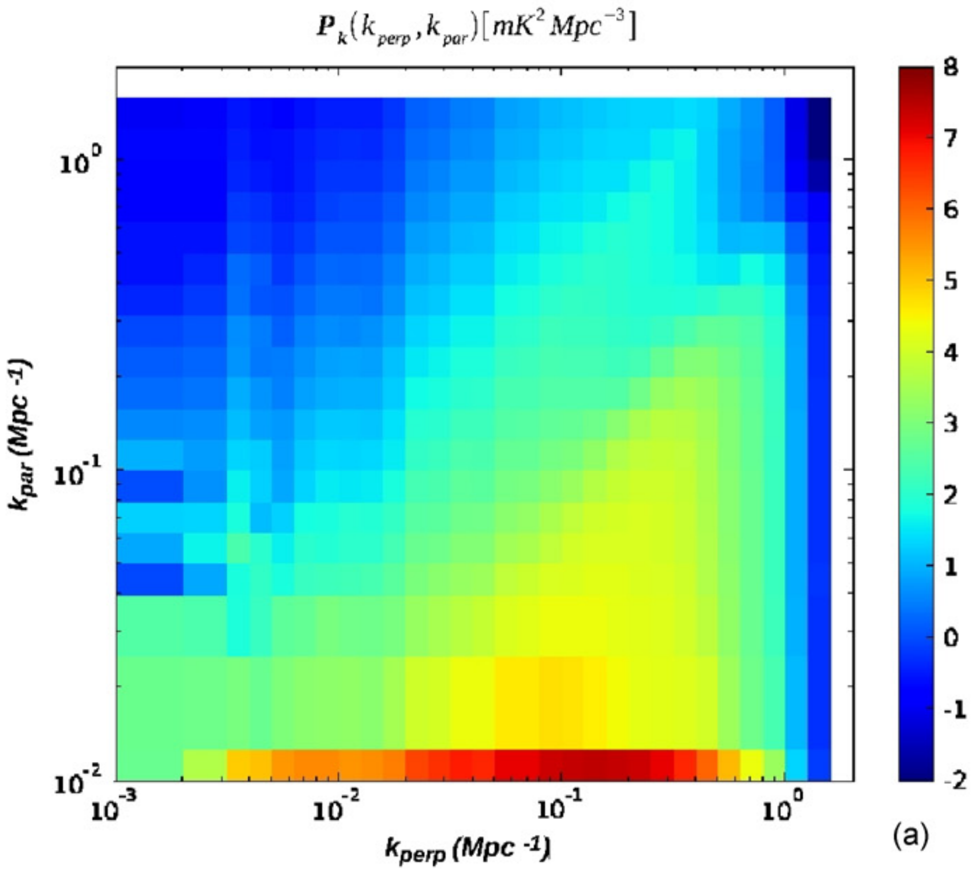
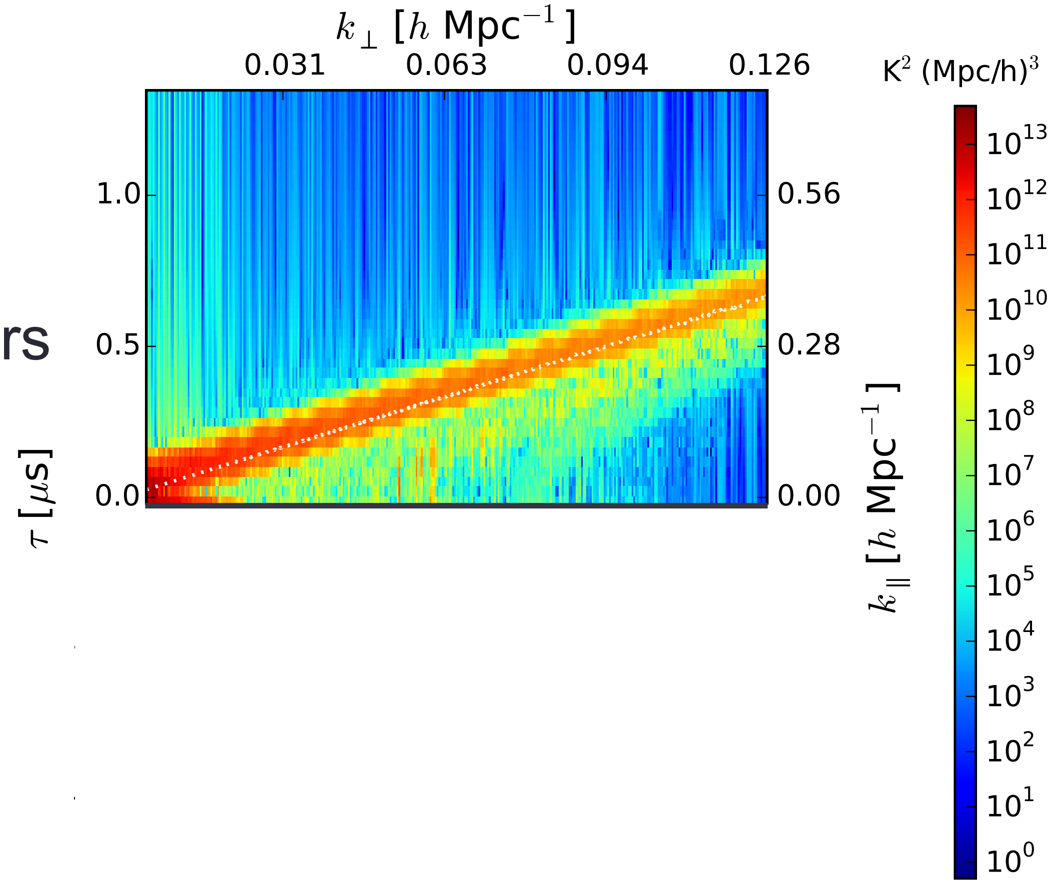


Datta *et al.* 2010

Data Simulation

- New effects discovered as simulations better reproduce interferometric data
- Datta et al. (2010) discovers *wedge* with floating-point visibility gridding
- Thyagarajan et al. (2015) discovers “edge brightening” by simulating horizon-to-horizon



Thyagarajan *et al.* 2015

PAPER Data

MWA Data

FHD [Sim]
(Sullivan, Hazelton)

PRISim
(Thyagarajan)

Cambridge
(Sims)

Berkeley
(Cheng)

FHD
(Sullivan)

PAPER
(Parsons, Ali)

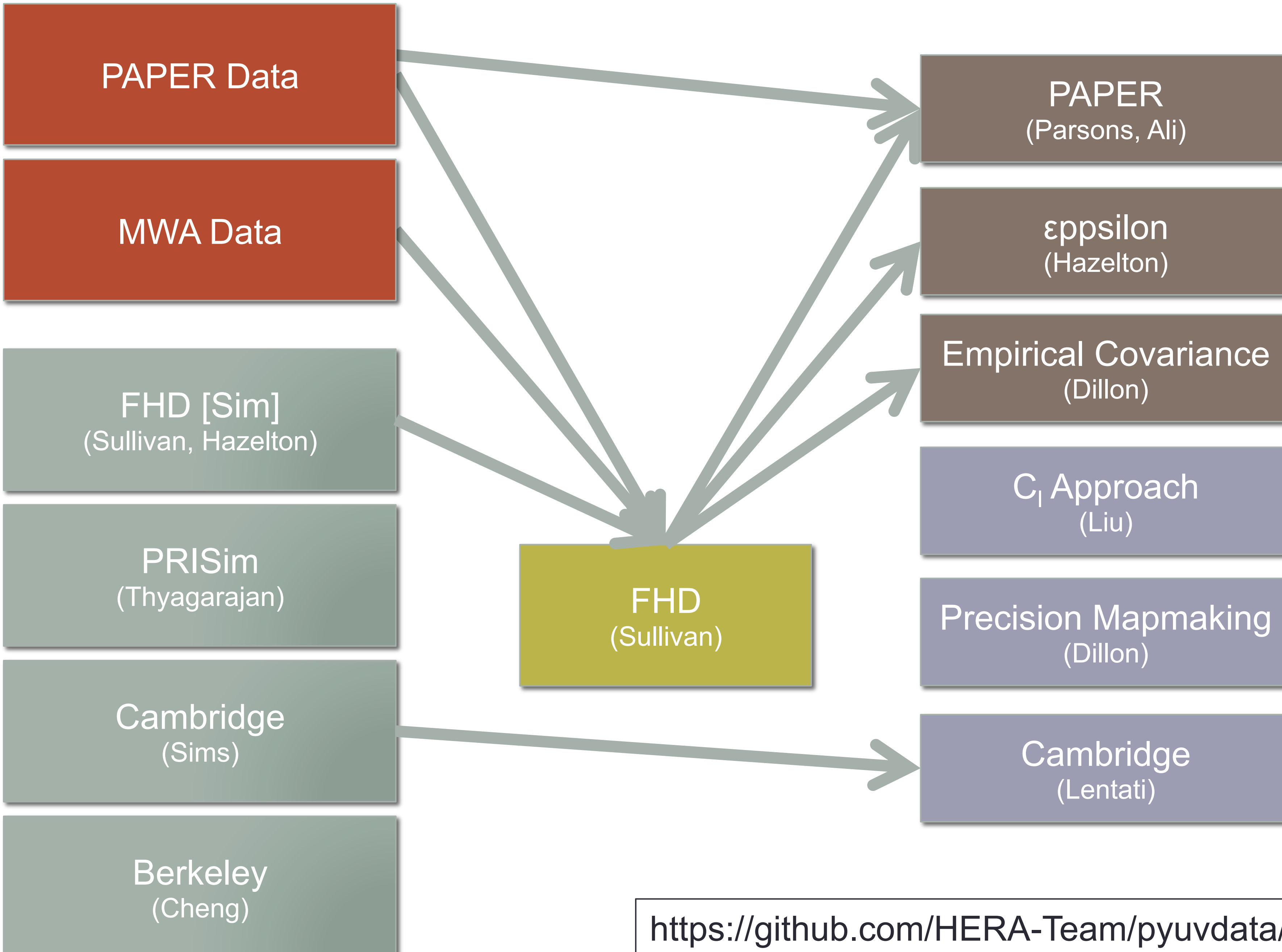
εppsilon
(Hazelton)

Empirical Covariance
(Dillon)

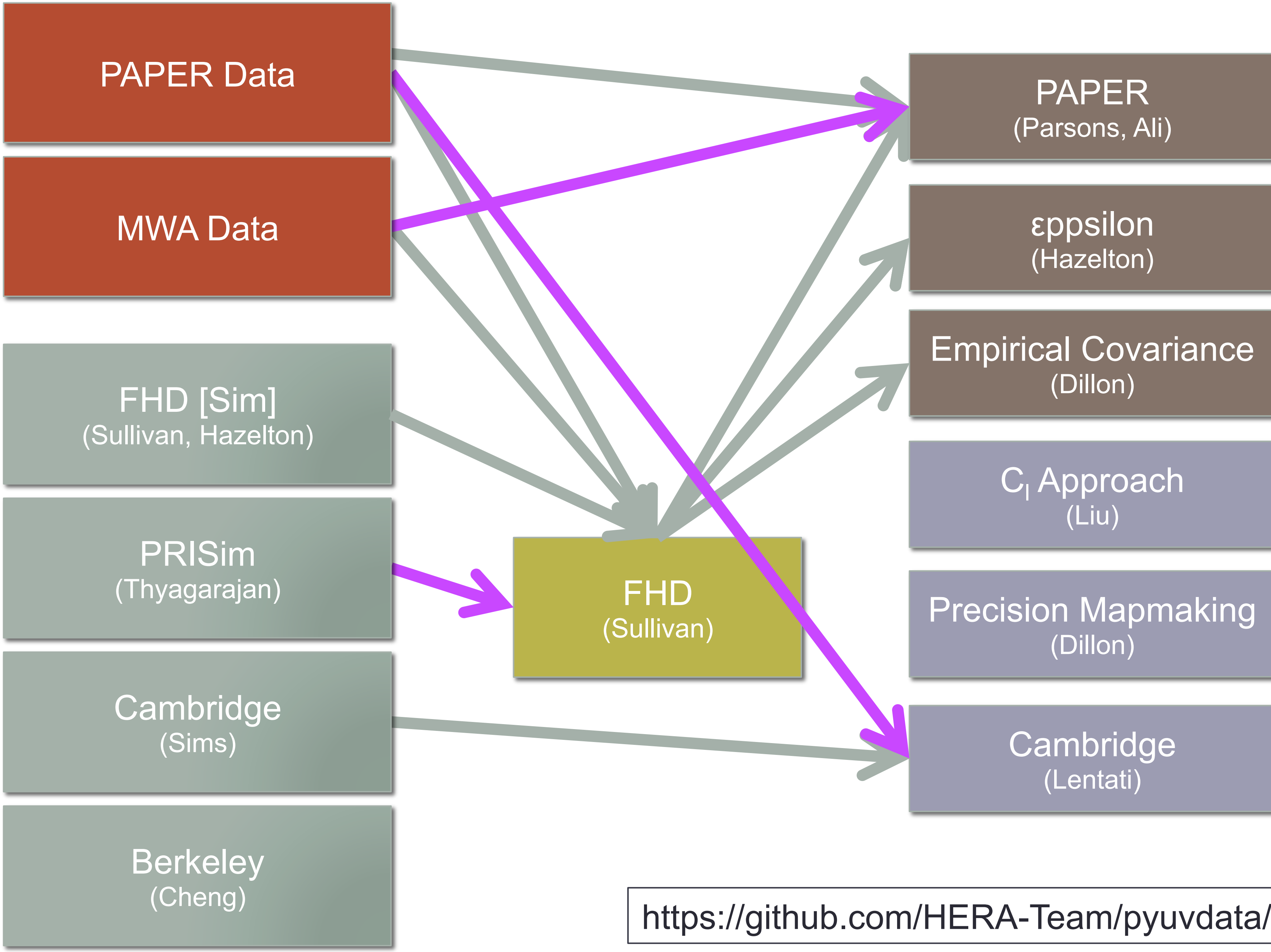
C_l Approach
(Liu)

Precision Mapmaking
(Dillon)

Cambridge
(Lentati)



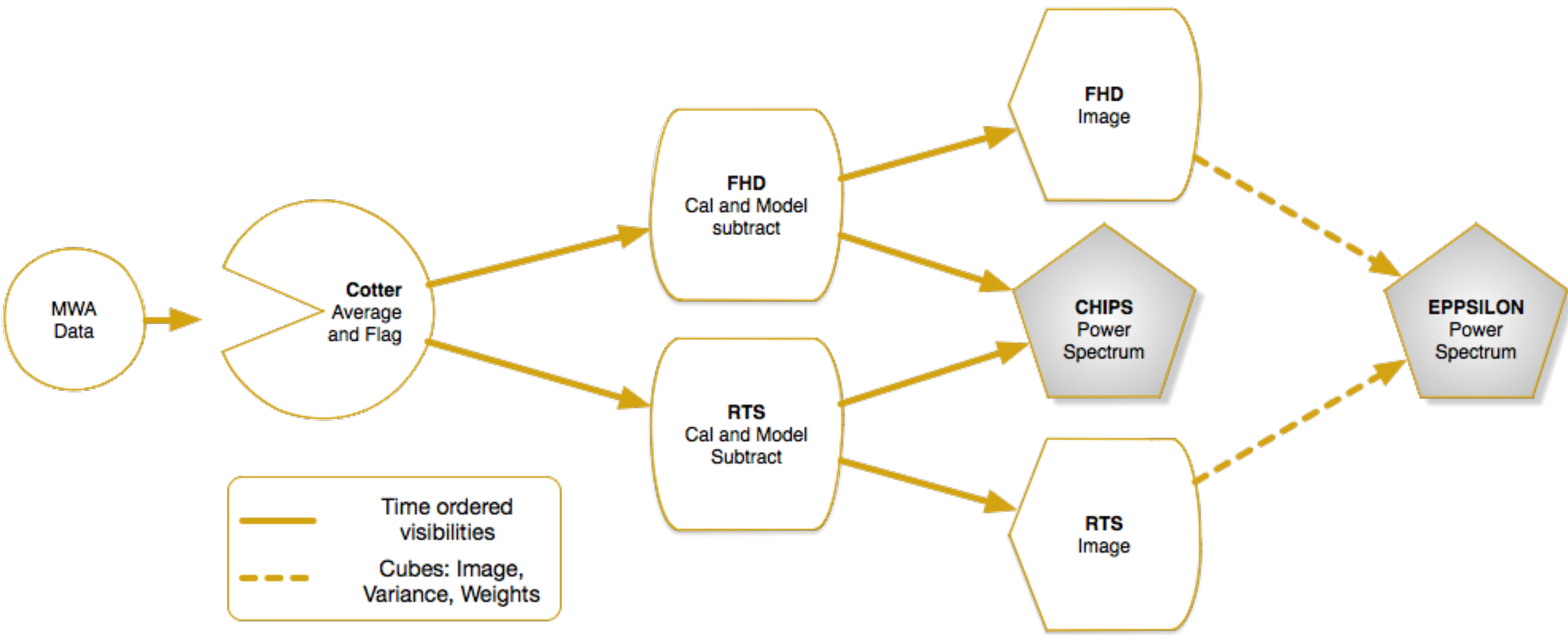
https://github.com/HERA-Team/pyuvdata/



https://github.com/HERA-Team/pyuvdata/

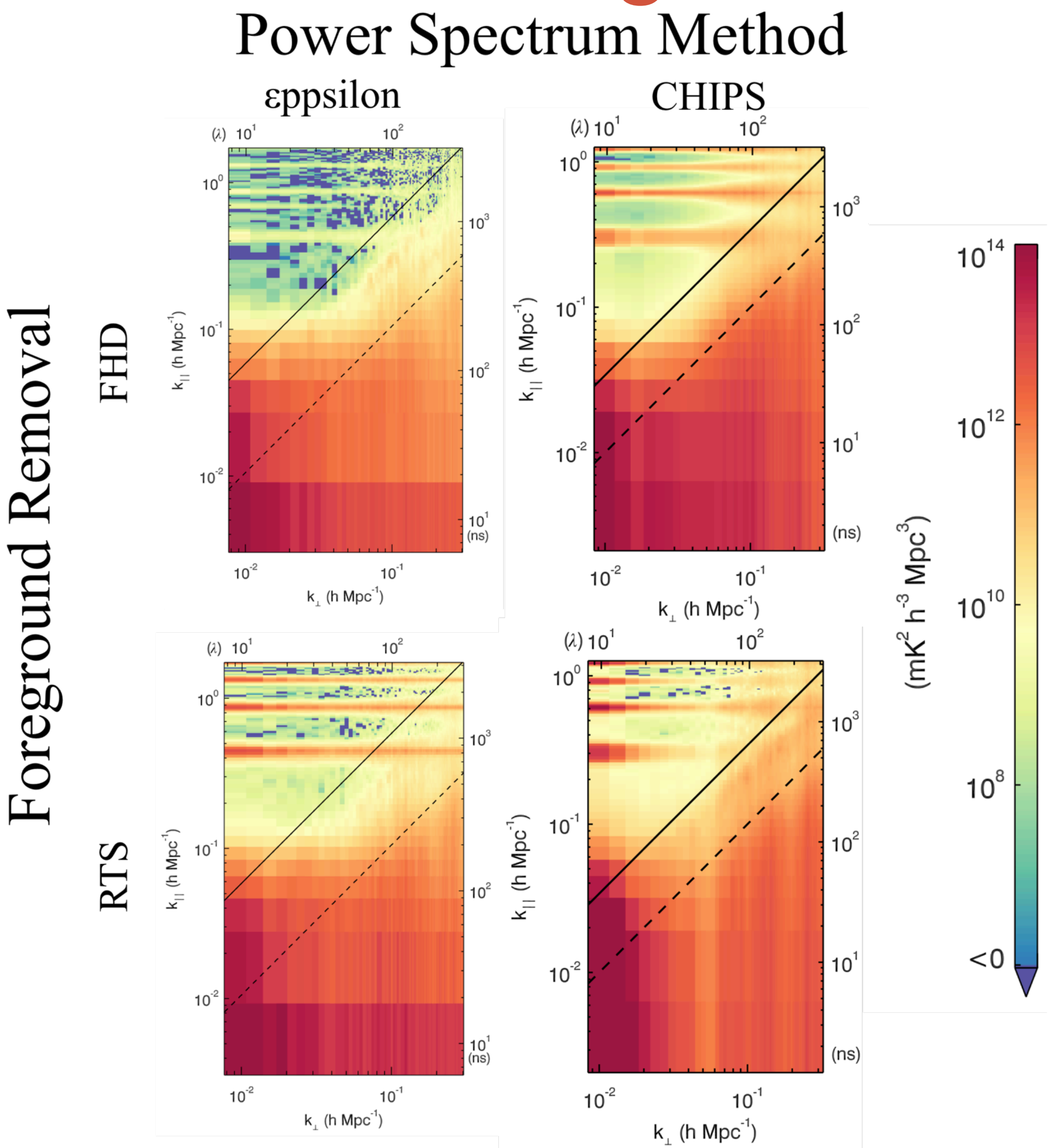
Multiple Pipelines

- MWA developing cross-linking between independent Australian and US pipelines



Jacobs *et al.* (2016)

Pipeline Cross-Linking



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MWA Collaboration

UNIVERSITY OF TORONTO

MIT

CfA

THE UNIVERSITY OF MELBOURNE

Raman Research Institute
Bangalore

ASU

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

CSIRO

Curtin University

UNIVERSITY of TASMANIA

ICRAR International Centre for Radio Astronomy Research

PERTH OBSERVATORY

THE UNIVERSITY OF SYDNEY

SWINBURNE
SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieve International Excellence

UWM
UNIVERSITY of WISCONSIN
MILWAUKEE

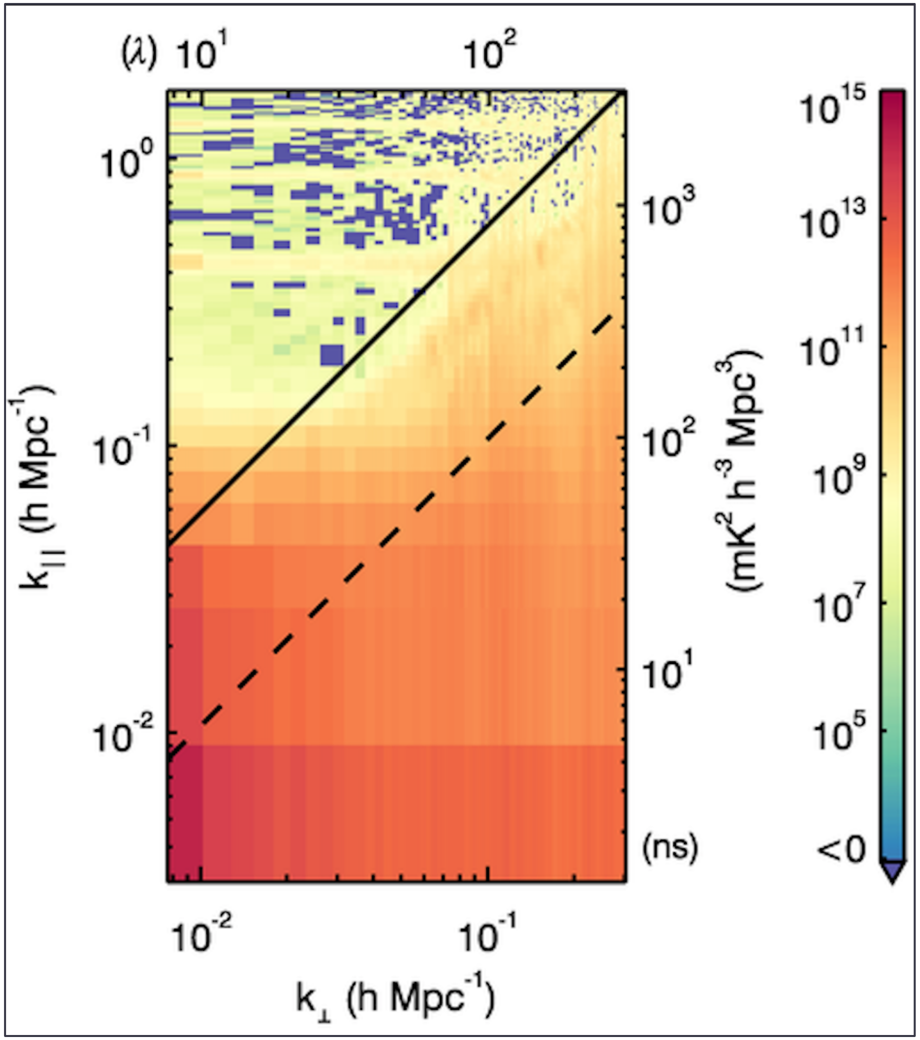
VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

UNIVERSITY OF WASHINGTON

The Murchison Widefield Array (MWA)

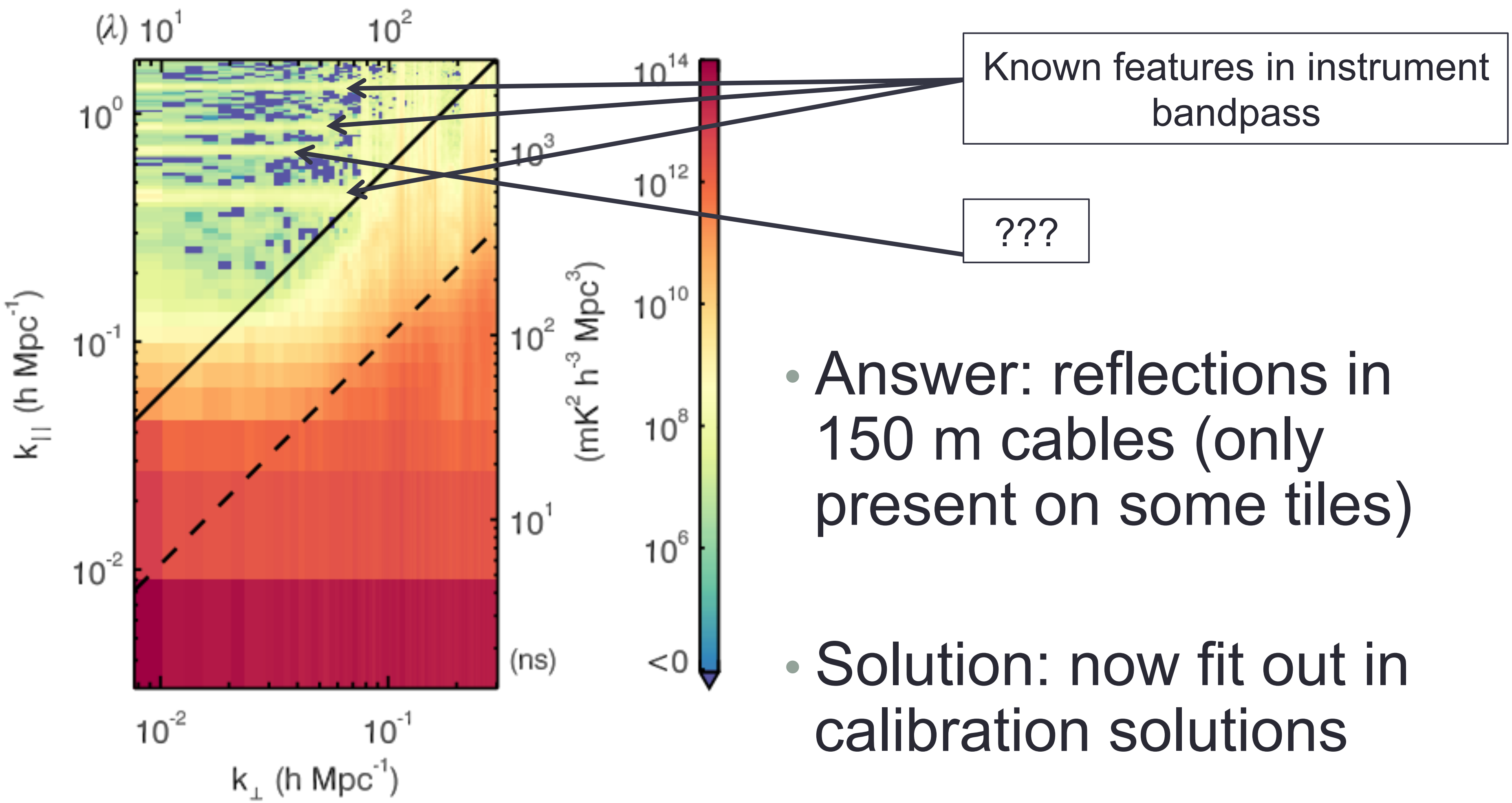
MWA EoR Project

- Custom built calibration/imaging (FHD) and power spectrum calculation (εppsilon) at UW
- Second pipe based in Australia
- Forward model foregrounds for calibration & subtraction
- 1000+ hours of data collected; approaching 400 on a single field
- Improve pipe methodically on small amounts of data
- New limits from 40 hours in Beardsley *et al.* 2016



Hazelton, Beardsley, Pober, *et al., in prep.*

Systematics Below the Imaging Limit



- Answer: reflections in 150 m cables (only present on some tiles)
- Solution: now fit out in calibration solutions

The Donald C. Backer Precision Array for Probing the Epoch of Reionization (PAPER)

U. Pennsylvania
- James Aguirre
- David Moore
- Saul Kohn

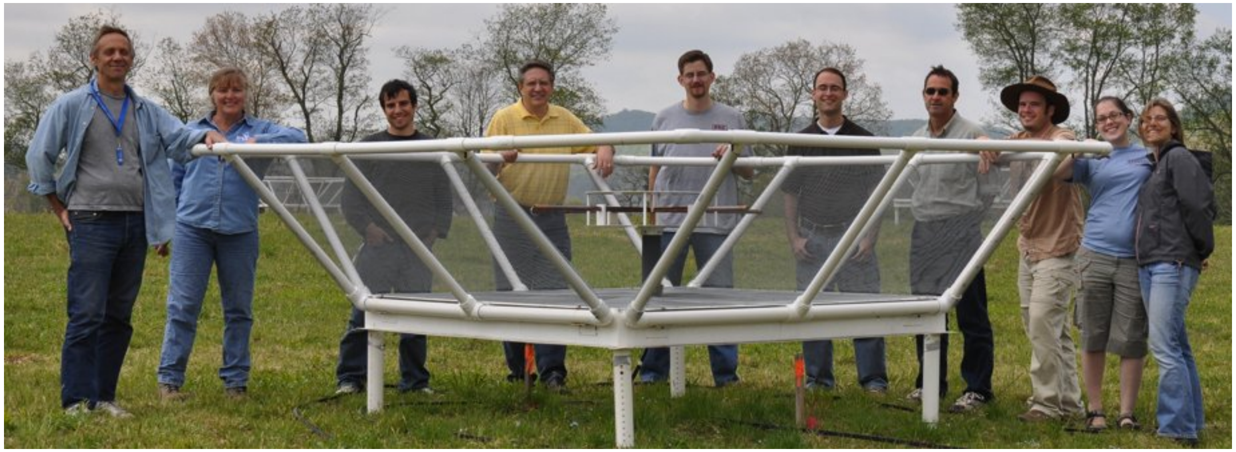
Brown U.
- Jonathan Pober

UC Berkeley
- Aaron Parsons
- Zaki Ali
- Dave DeBoer
- Dave MacMahon
- Adrian Liu
- Carina Cheng

U. Virginia / NRAO
- Rich Bradley
- Chris Carilli
- Pat Klima
- Nicole Gugliucci

Arizona State U.
- Daniel Jacobs

SKA South Africa
- Gianni Bernardi
- Rhidima Nunhokee




Kgalagadi
Southern
Johannesburg
Mpumalanga
North West
Swaziland
Karas
Kimberley
Free State
KwaZulu-Natal
Northern Cape
D'Urban
Lesotho
Karoo Astronomy Reserve
Carnarvon
South Africa
Eastern Cape
Western Cape
Port Elizabeth
Stellenbosch
Cape Town

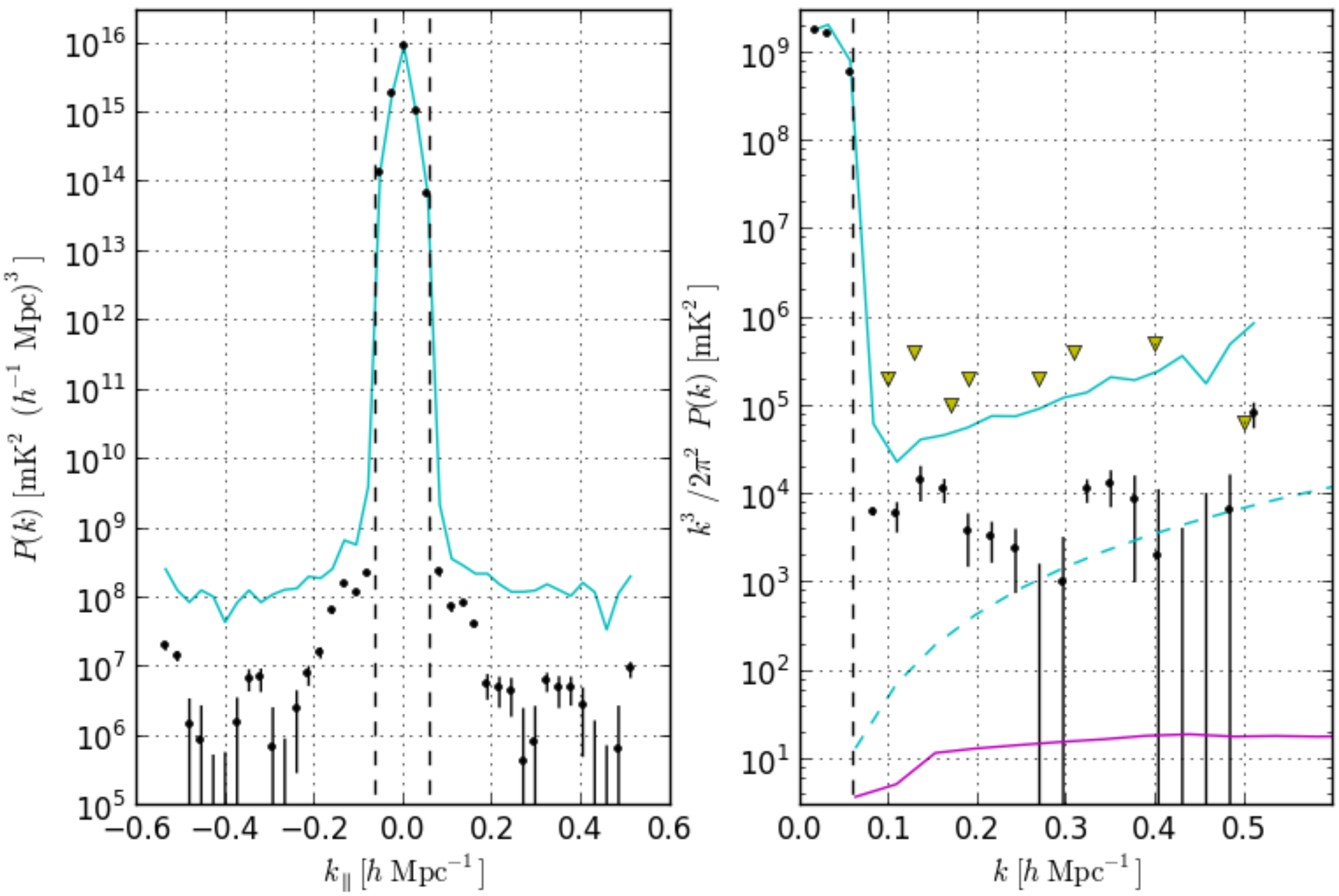
The Precision Array for Probing the Epoch of Reionization (PAPER)

- **One goal**: detect the power spectrum of 21 cm emission from the EoR

- Redundant configuration improves power spectrum sensitivity: measure the same Fourier mode multiple times! (Parsons, Pober, *et al.* 2012a)

- Little imaging capabilities – *foreground avoidance* vs. *foreground subtraction* (Parsons, Pober, *et al.* 2012b)

PAPER 32 upper limit: $(41\ \mathrm{mK})^2$ at z = 7.7

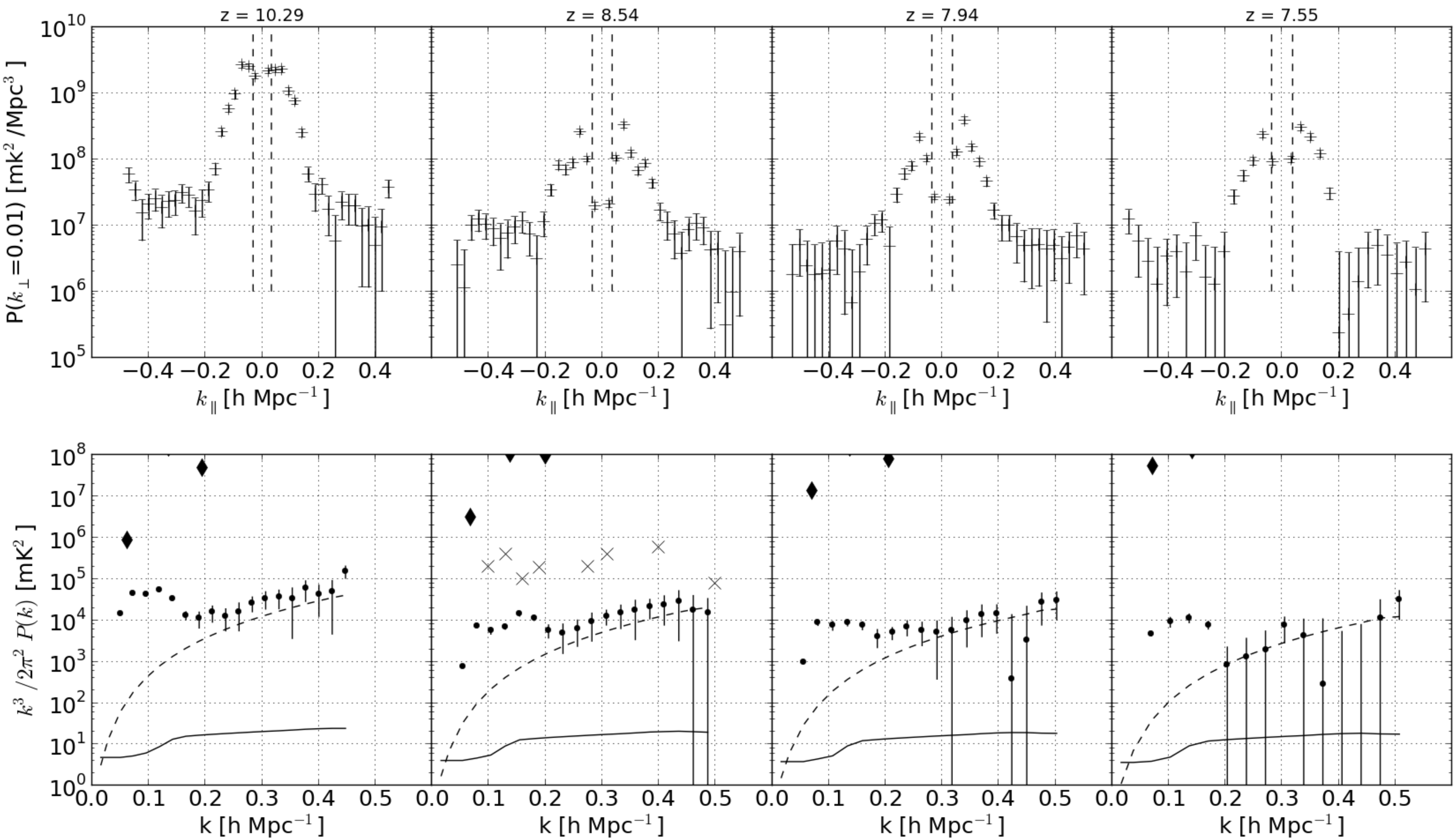


Parsons *et al.* (2014)

Multi-redshift results

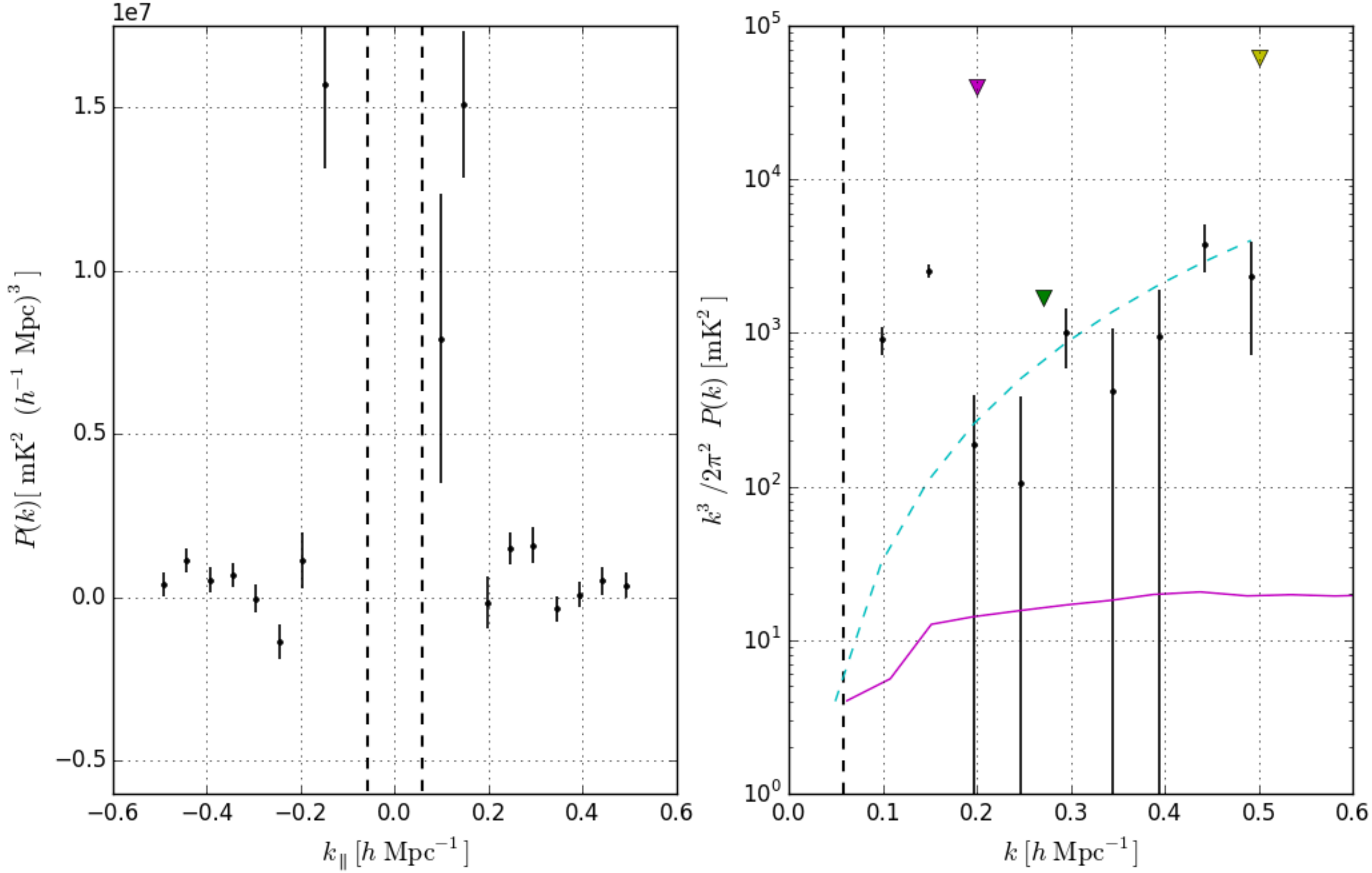
MWA (Dillon *et al.* 2014)

GMRT (Paciga *et al.* 2013)



Jacobs, Pober, *et al.* (2014)

PAPER 64 upper limit: $(22\ \mathrm{mK})^2$ at $z = 8.4$



Ali *et al*. (2015)

Two Critical Paths Forward

- Making the most out of first generation experiments
  - More rigorous testing (data simulation, multiple pipelines)
  - Continued analysis (and cross-analysis) of existing data sets
- Building on lessons learned for second generation experiments

What's Next?

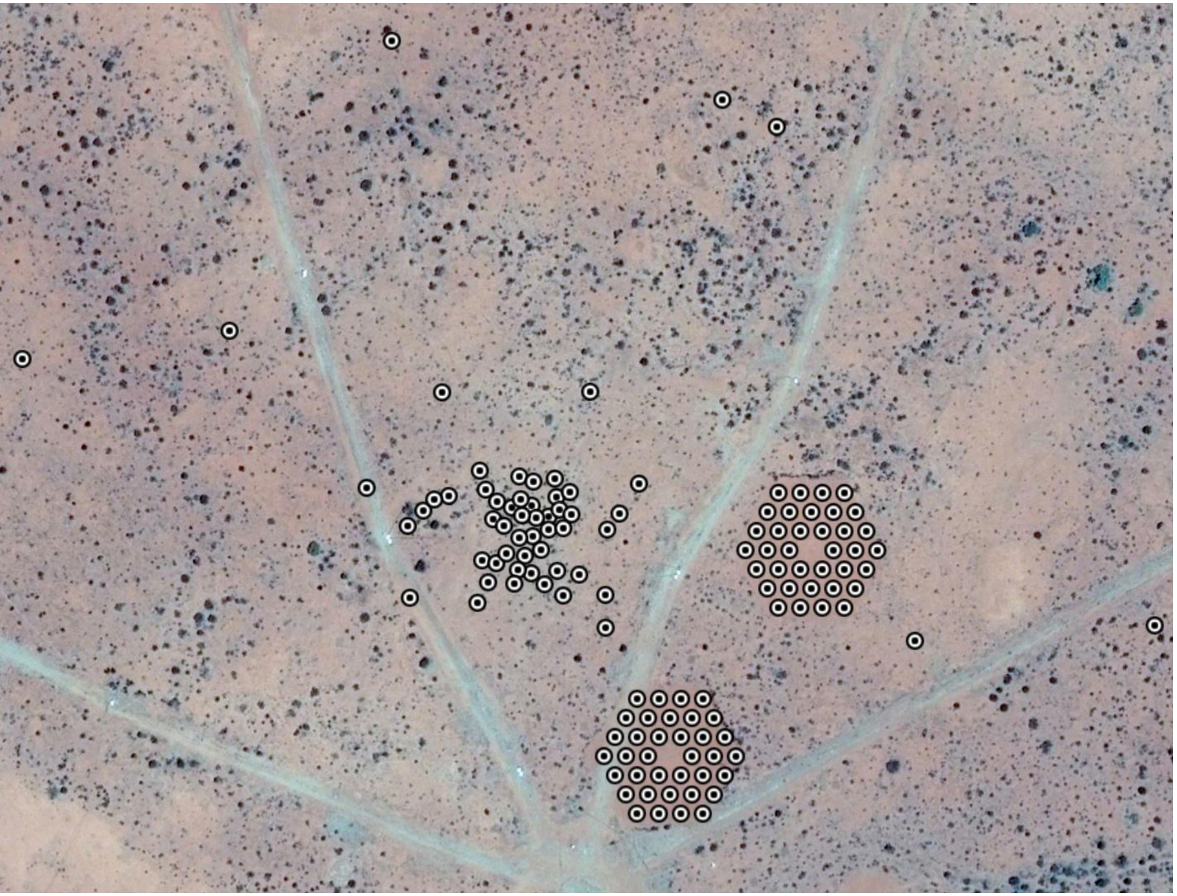
MWA

- MWA EoR project continuing
- MWA expansion
  - Phase II: 256 tiles
  - Phase III: improved passband, more tiles?

PAPER

- PAPER finished observations April 1, 2015
- 2 seasons of PAPER 128 being analyzed
- PAPER refurbishment to become HERA

MWA Phase II



- Addition of two redundant hexagonal cores in summer 2016
- First array that will allow us to simultaneously test sky-based and redundant calibration for EoR studies

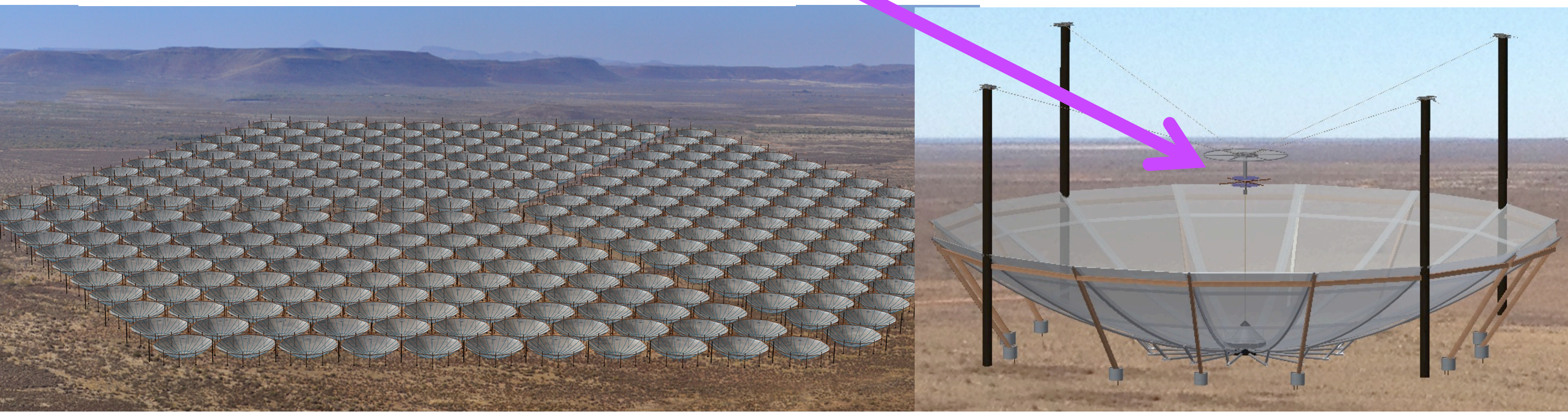
Construction Complete Commissioning Underway!

Brown Grad Students: Adam Lanman, Josh Kerrigan, and Wenyang Li

- First redundant calibration achieved last week by Wenyang Li
- Comparison with sky-based calibration underway!

HERA (Hydrogen Epoch of Reionization Array)

Modified PAPER Dipole



- **Sensitivity**: 14 m reflector design significantly boosts PAPER dipole collecting are

- **Analysis:** De l improved foreground re

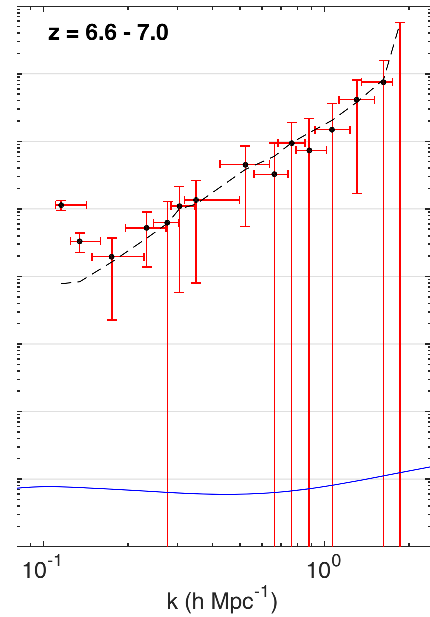
- **Chromaticity** ys below *k*-modes of interest

2016 papers by Neben, Ewall-Wice, Patra, and Thyagarajan

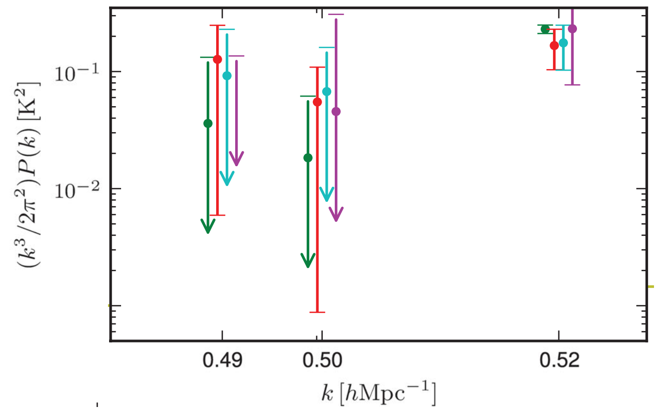
The Importance of Sensitivity

- Every published 21 cm limit detected *something*
- With moderate significance – how can you jackknife?

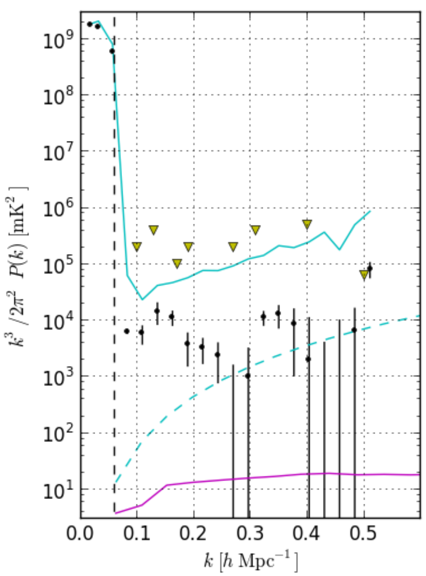
Dillon *et al.* 2015



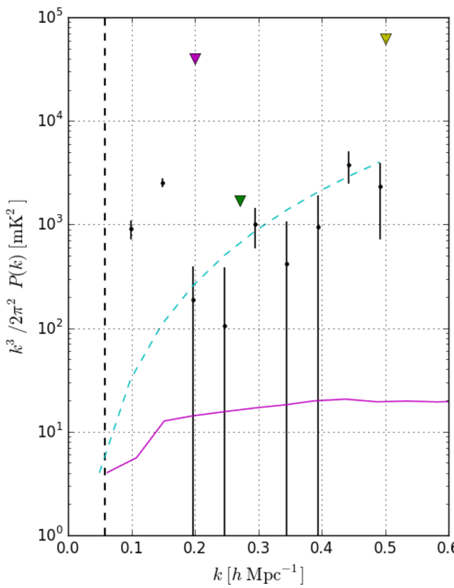
Paciga *et al.* 2014



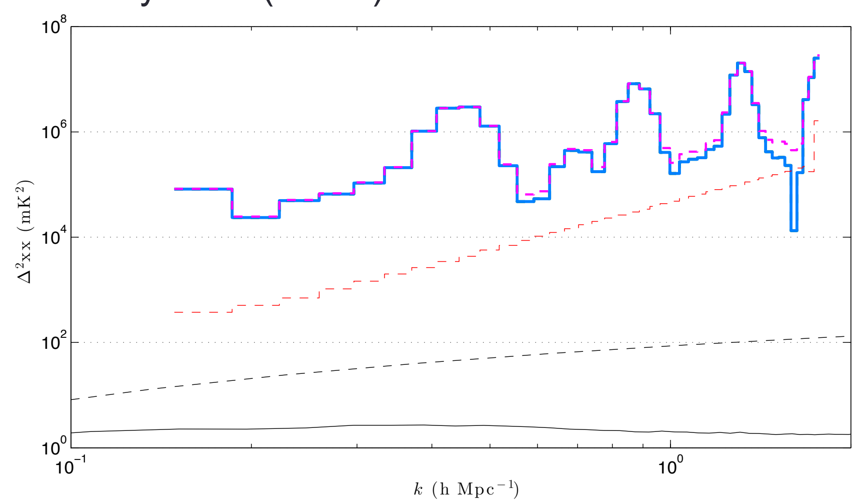
Parsons *et al.* 2014



Ali *et al.* 2015

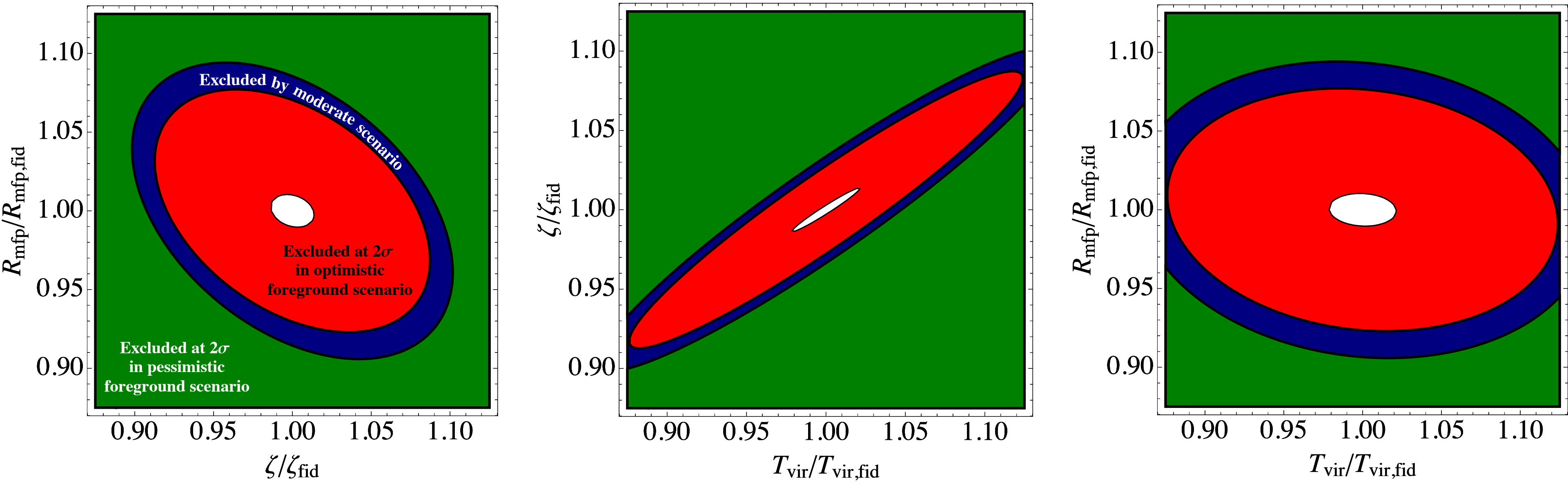


Beardsley 2015 (thesis)



Constraining Astrophysics of the EoR

Joint fits over all redshifts

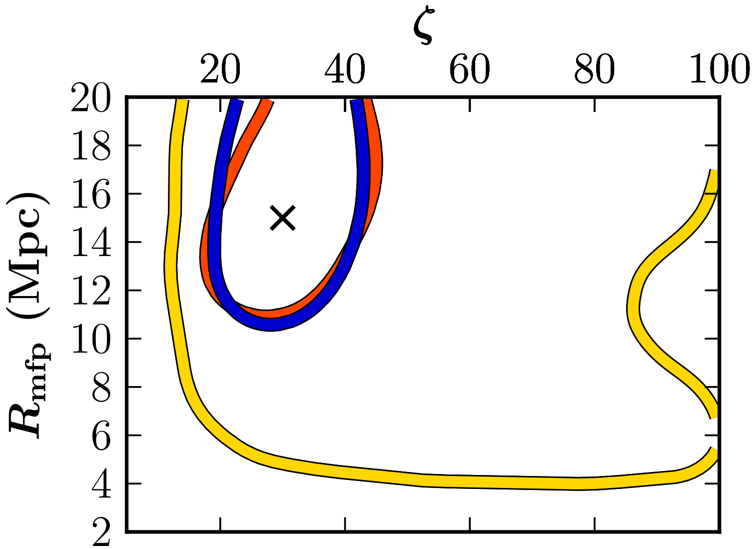


- Optimistic level constraints (100σ+) reduce errors to < 5 % level
  - Much higher accuracy than likely possible!

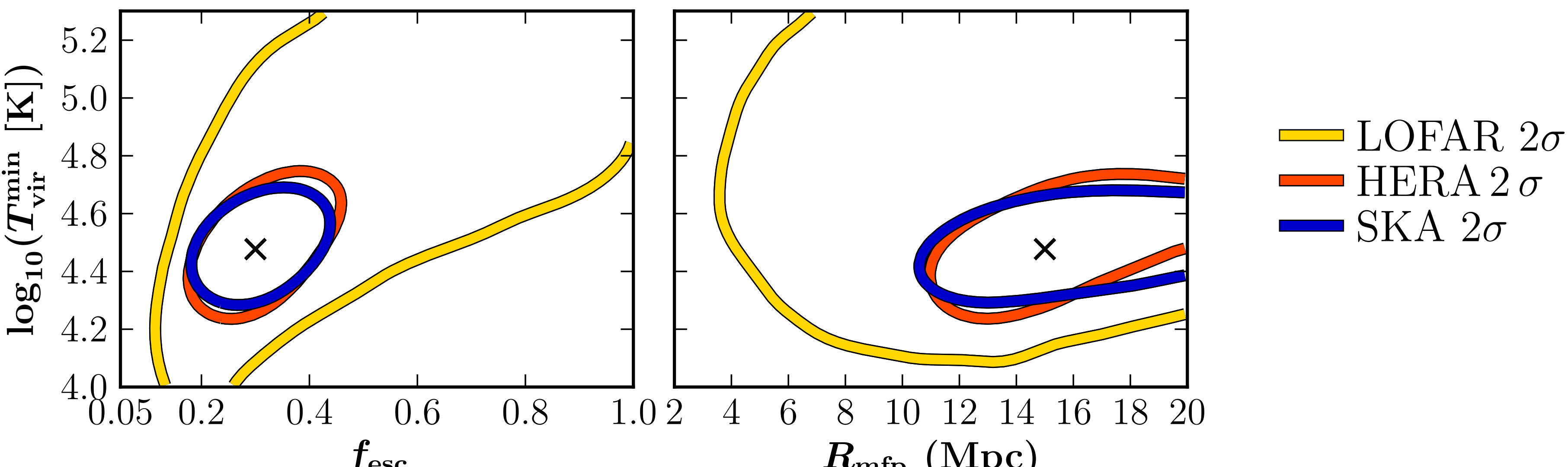
- Foreground subtraction is valuable for recovering physics

Pober *et al*. (2014)

Constraining Astrophysics of the EoR

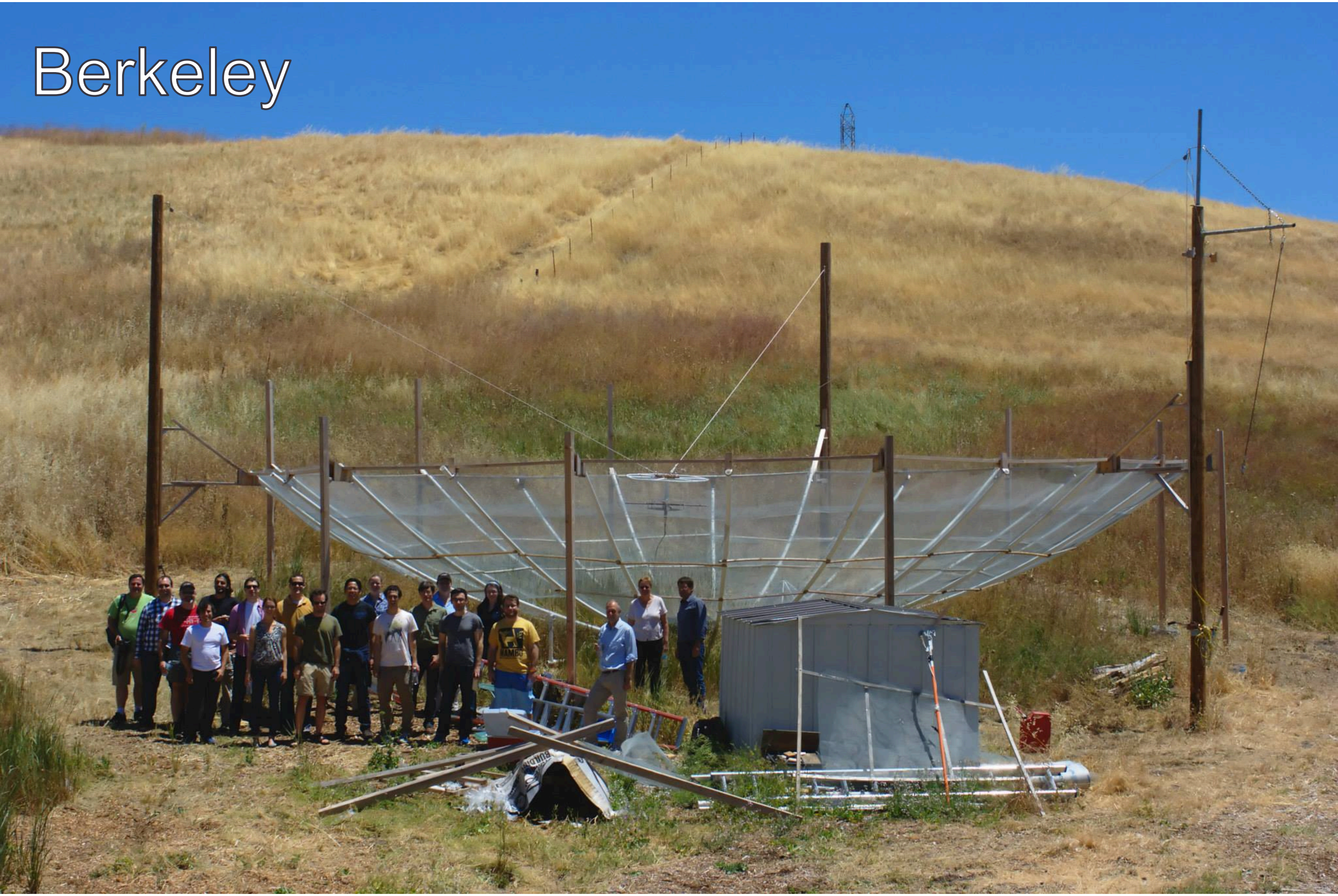


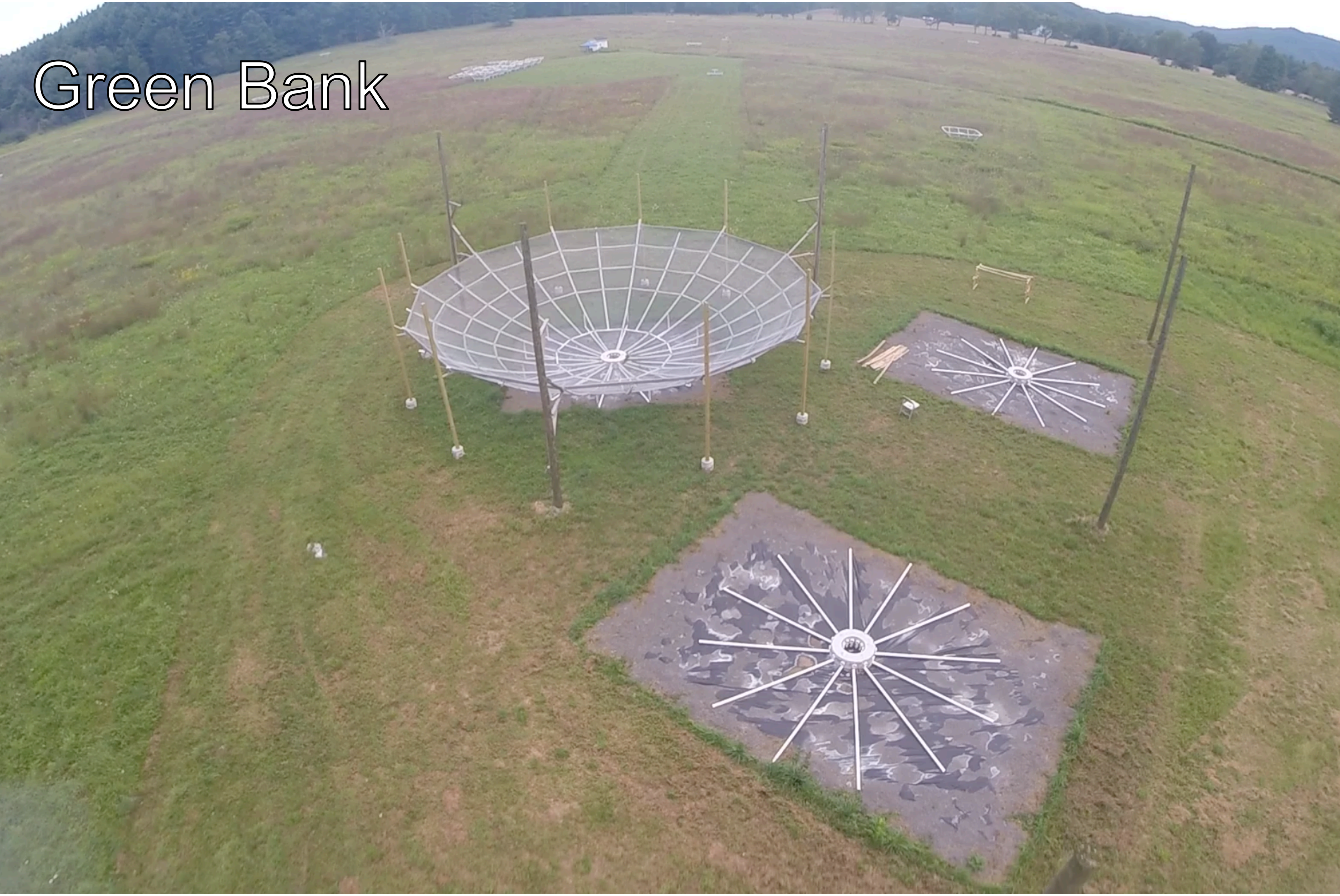
Instrument (multi-z)	Parameter Estimate (% uncertainty) $\frac{\zeta}{\zeta_{fid}}$	$\frac{R_{mfp}}{R_{fid,mfp}}$	$\frac{\log_{10}(T_{vir}^{min})}{\log_{10}(T_{vir,fid}^{min})}$
LOFAR	1.55 (43.3%)	0.89 (31.1%)	1.06 (6.1%)
HERA	1.03 (12.0%)	1.01 (12.4%)	1.00 (2.0%)
SKA	1.02 (9.4%)	1.04 (13.5%)	1.00 (1.3%)



Greig and Mesinger *et al.* (2015)

Berkeley




Green Bank


South Africa

Fully funded as of 9/12

Commissioning underway, expansion to 37 starting soon!

Acknowledgements & Collaborators

Faculty
James Aguirre
Don Backer
Gianni Bernardi
Judd Bowman
Rich Bradley
Steve Furlanetto
Jackie Hewitt
Matt McQuinn
Andrei Mesinger
Miguel Morales
Aaron Parsons
Max Tegmark

Postdocs
Adam Beardsley
Josh Dillon
Bradley Greig
Danny Jacobs
Lindley Lentati
Adrian Liu

Research Staff
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Dave DeBoer
Matt Dexter
Bryna Hazelton
Dave MacMahon
Bart Pindor
Ian Sullivan
Cath Trott

Graduate Students
Zaki Ali
Nichole Barry
Patti Carroll
Carina Cheng
Josh Kerrigan
Matt Kolopanis
Adam Lanman
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David Moore
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U.S. Air Force Office of Scientific Research

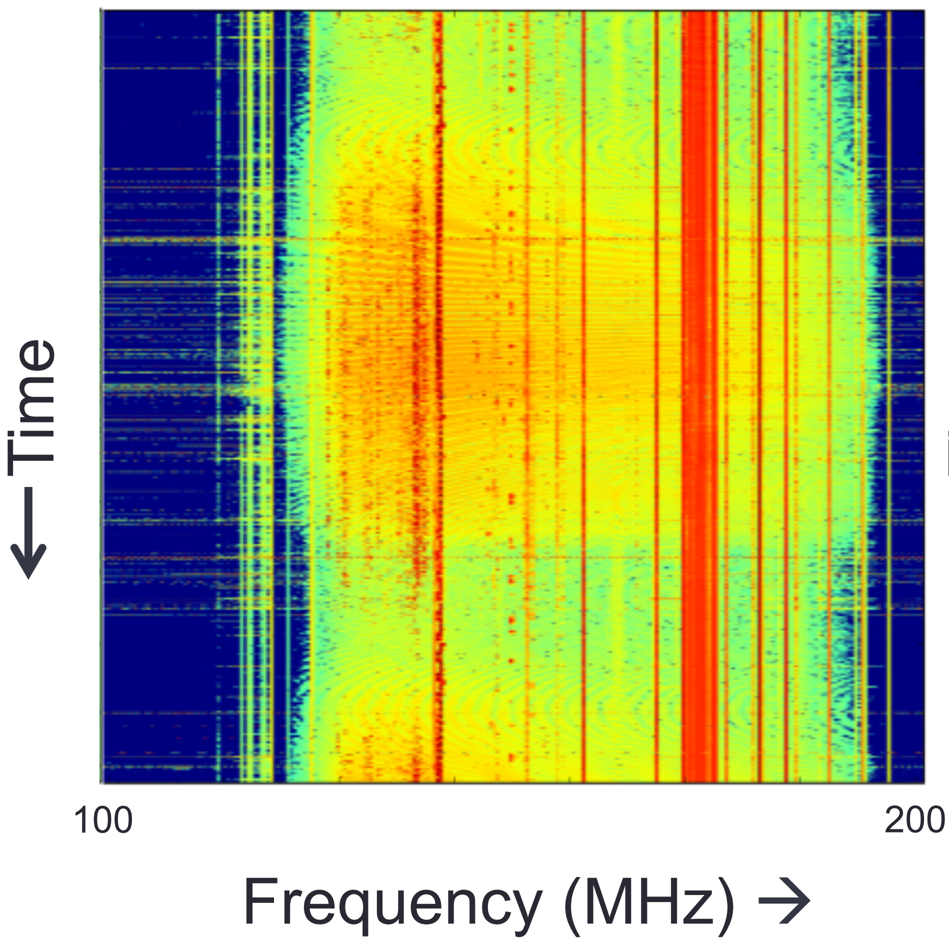
Other
SKA South Africa
The Wajarri Yamatji People

Thanks!

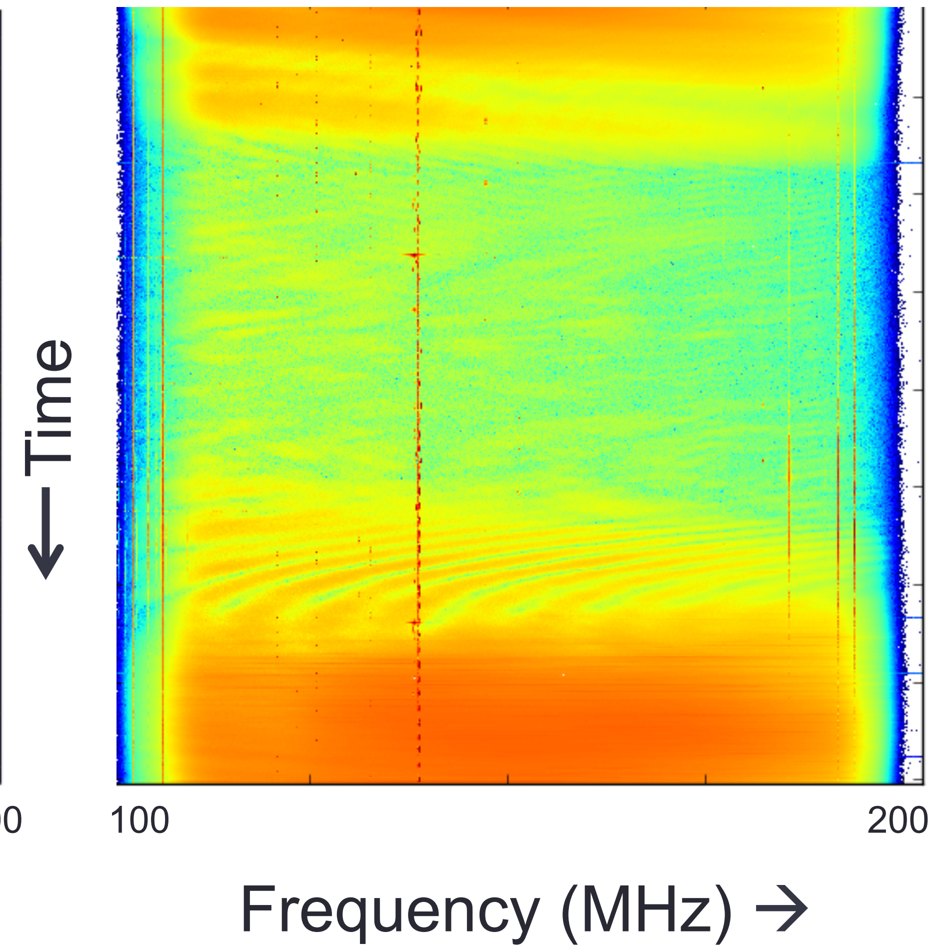
EXTRA SLIDES

Radio Frequency Interference (RFI)

Green Bank, WV

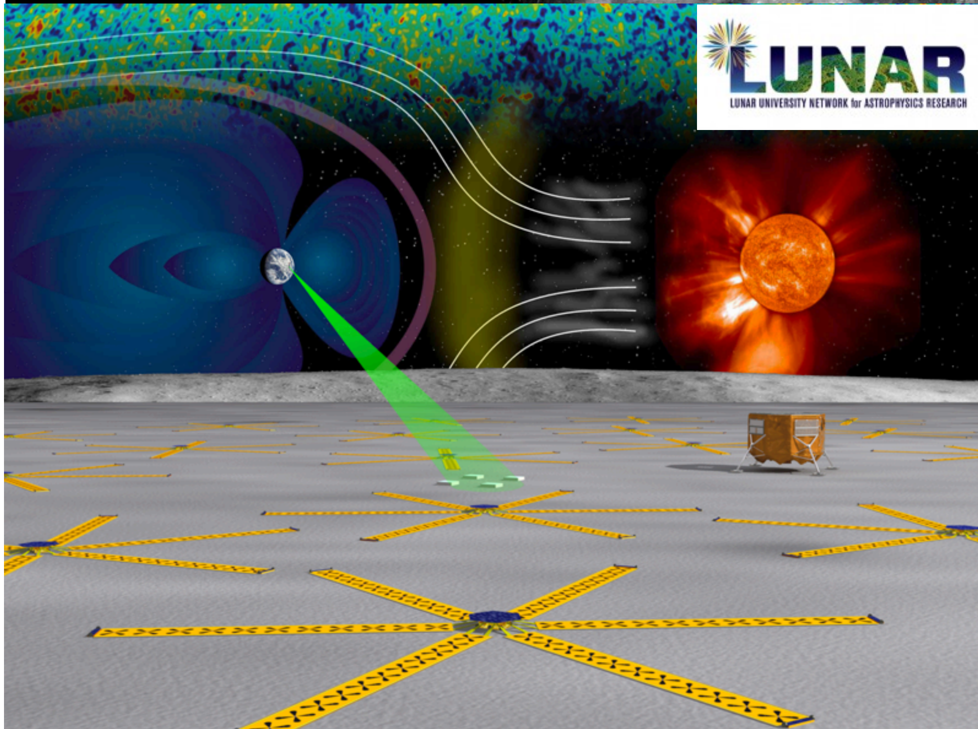


Karoo Desert, SA

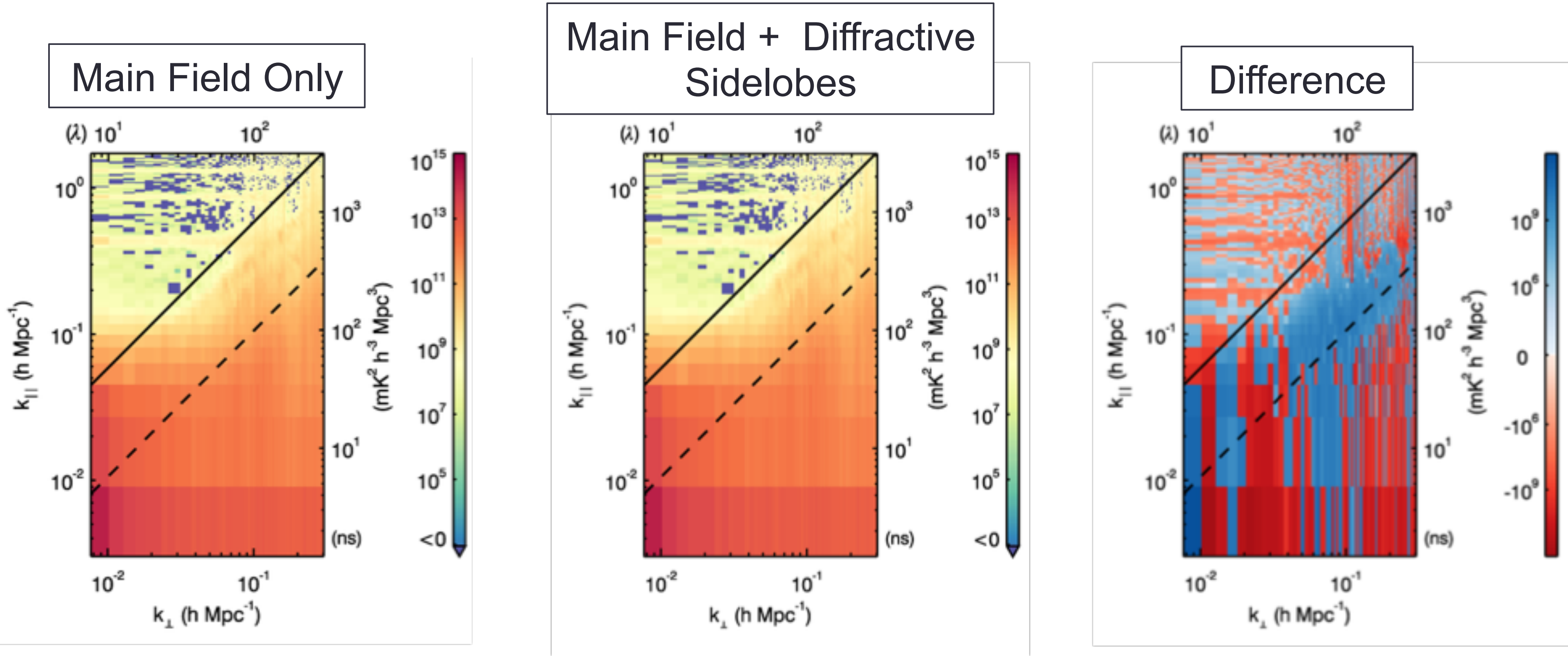


Ionosphere

- Opaque to radio waves below 10 ~ 50 MHz (depending on conditions)
  - Limits dark ages science from the earth
- Refractive effects in EoR band adds extra degree of difficulty



Improving Foreground Models



- Jackknife tests new algorithms, foreground models
- Including sources *away* from primary field of view improves high $k_{||}$ modes

Pober *et al.*, 2016

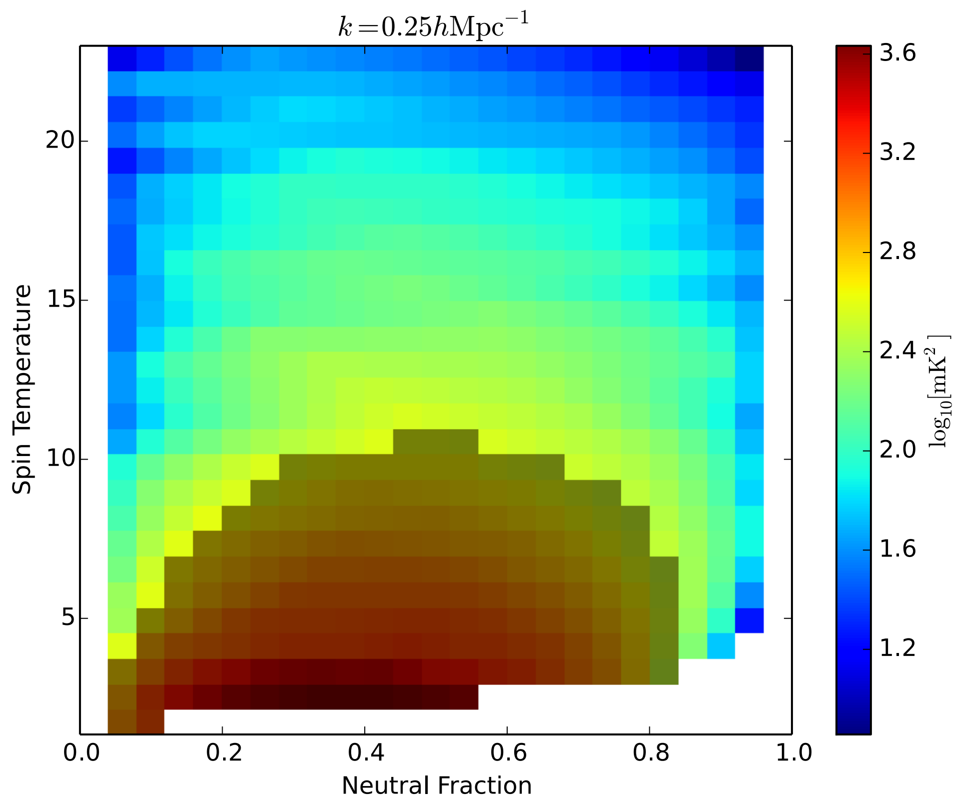
Cold reionization

$$\delta T_b(\nu) \approx 9 x_{\rm HI} (1+\delta)(1+z)^{\frac{1}{2}} \left[1 - \frac{T_{\rm CMB}(z)}{T_S}\right] \left[\frac{H(z)/(1+z)}{{\rm d}v_{\parallel}/{\rm d}r_{\parallel}}\right] {\rm mK}$$

- Power spectrum brightness can be dominated by small T_S
- T_S strongly coupled to *physical* gas temperature: need cold IGM

IGM Temperature Limits

- 21cmFAST simulations to explore parameter space T_S vs. x_{HI}
- Gray region ruled out at 95% confidence by PAPER measurements



Pober *et al.* (2015)

Heating the universe

- Fiducial $T_K >> T_{CMB}$
- How much heat do the *observed* high z galaxies provide?
  - Depends on 3 parameters: f_X, f_{abs}, $\dot{\rho}_{SFR}$
- PAPER constraints cut into parameter space

Pober *et al*. (2015)

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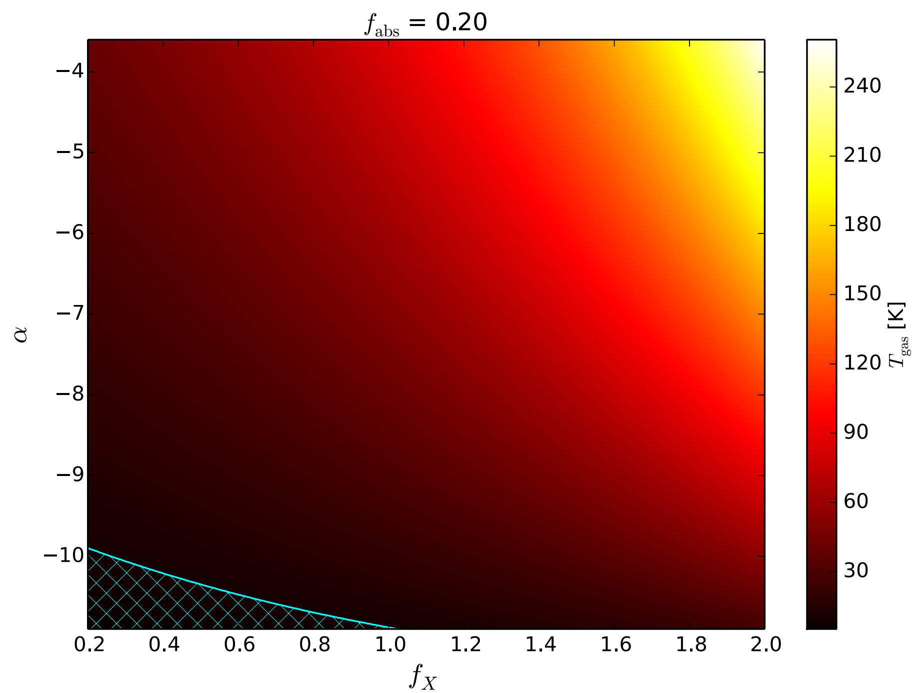

Pober *et al.* (2015)

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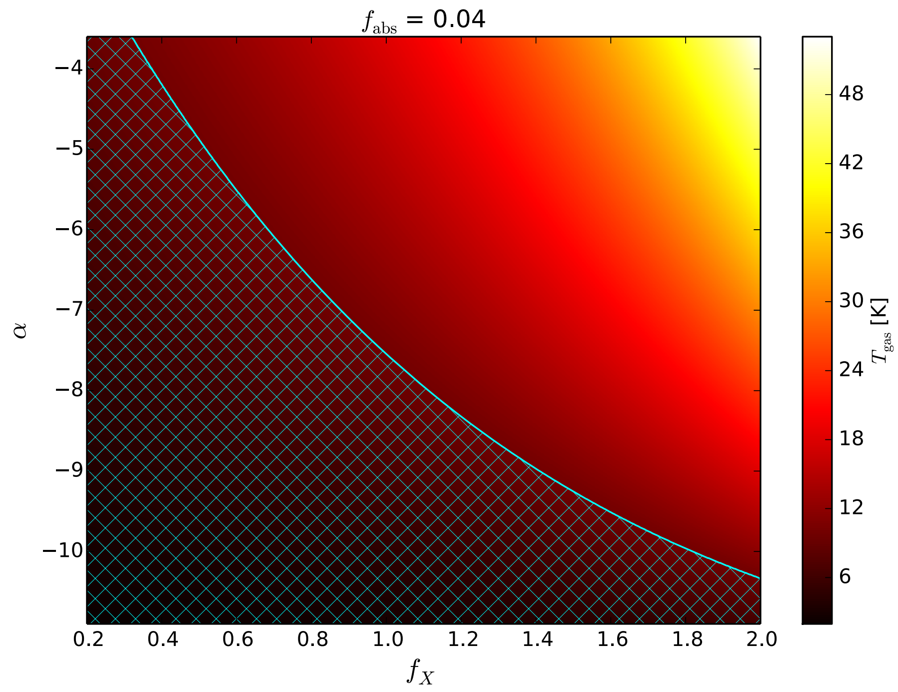
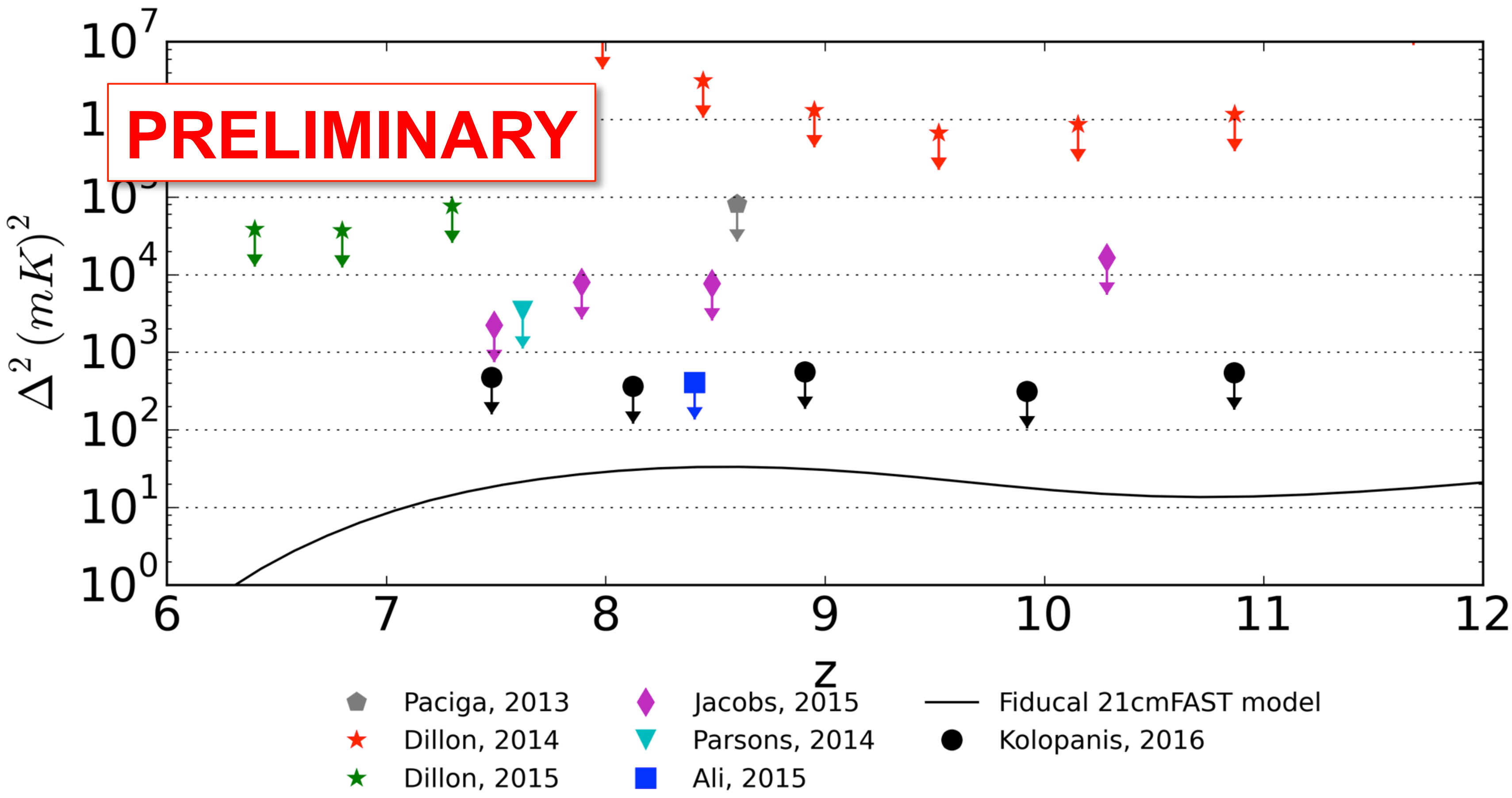
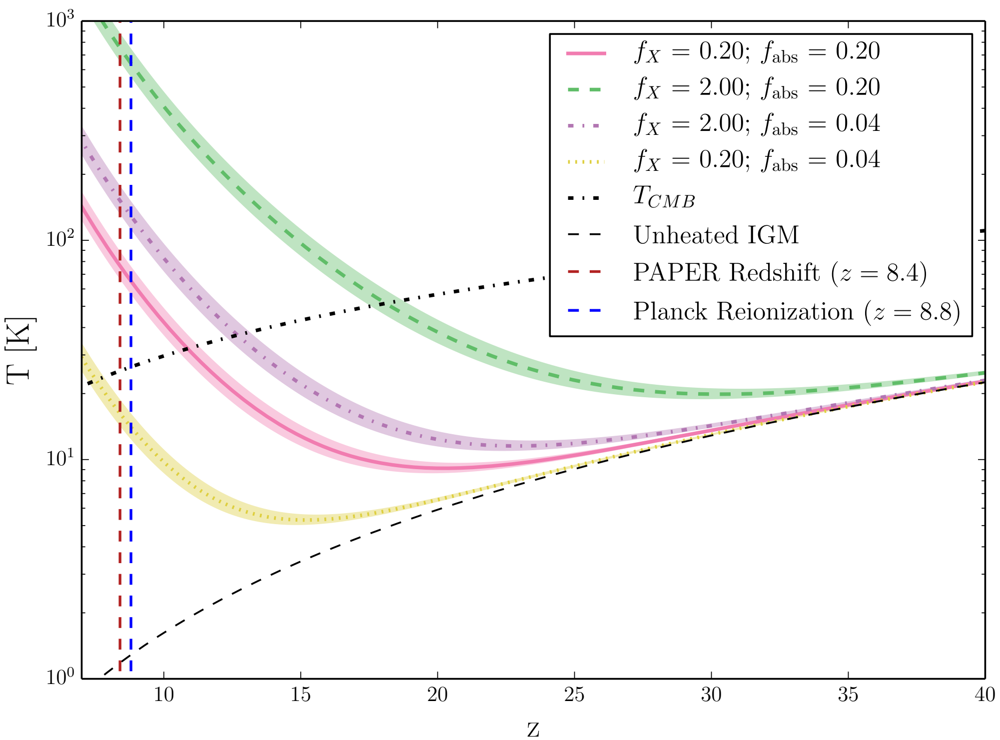


Pober *et al.* (2015)

State of the Art



Self-consistent model

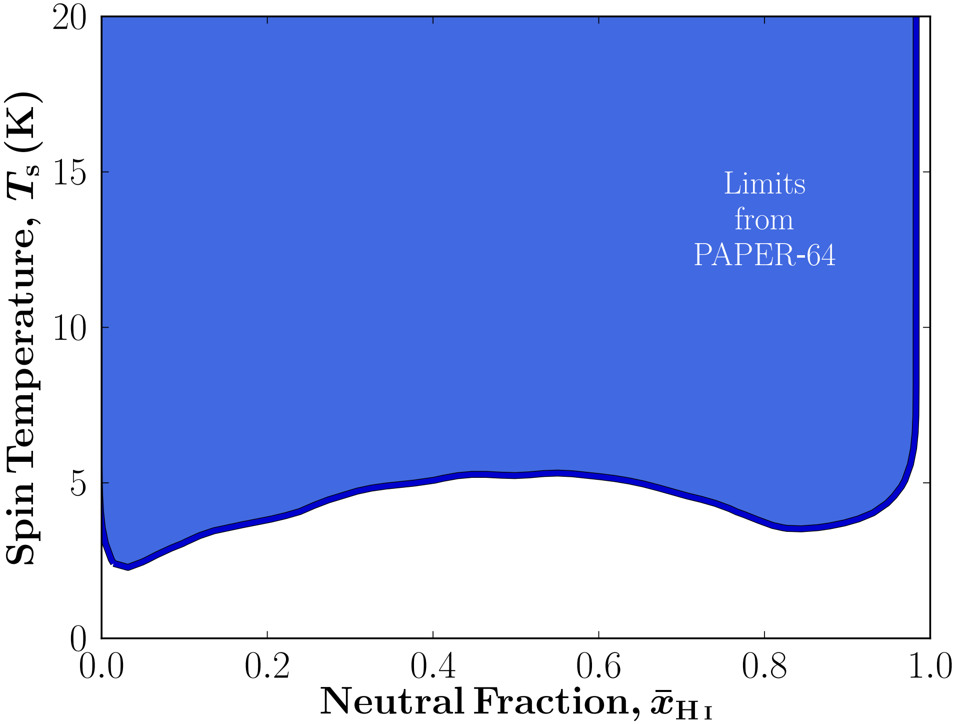


- Galaxy population that can reionize the universe (Robertson *et al.* 2015)
- Minimally efficient heating (e.g. Fialkov *et al.* 2014) brings IGM above PAPER limits

Pober *et al.*, arXiv:1503.00045

MCMC Constraints

- 21CMMC (Greig & Mesinger 2015) explores reionization model parameter space efficiently
- Marginalizing over reionization parameters lowers T_S limits
- Including other priors (McGreer *et al.* 2015 + Planck) helps



Greig, Mesinger & Pober (2016)

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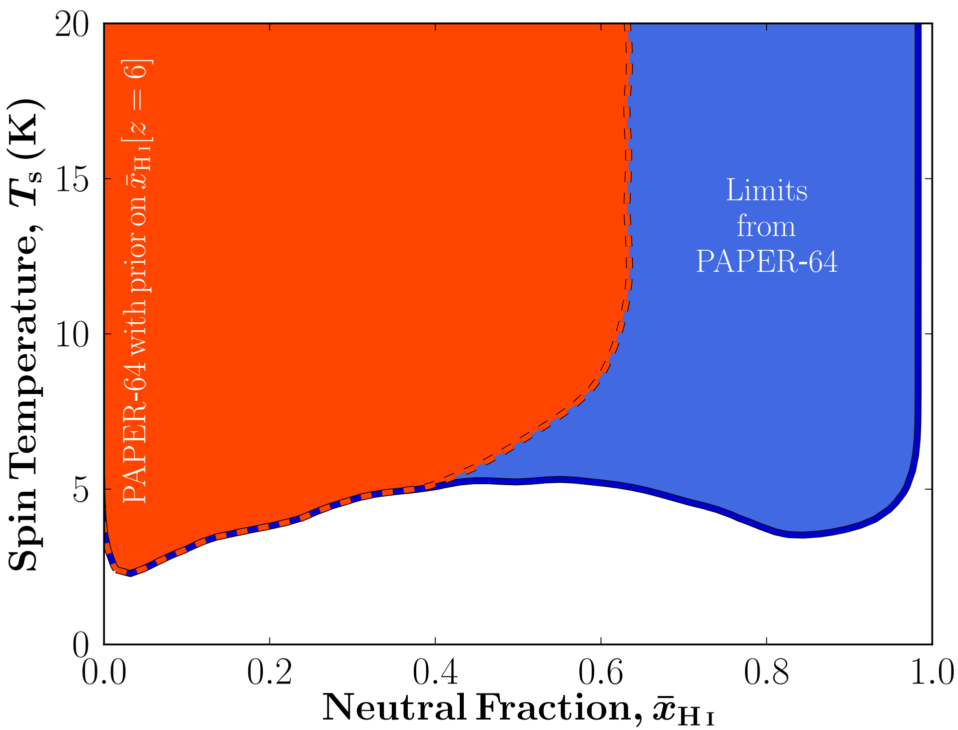

Greig, Mesinger & Pober (2016)

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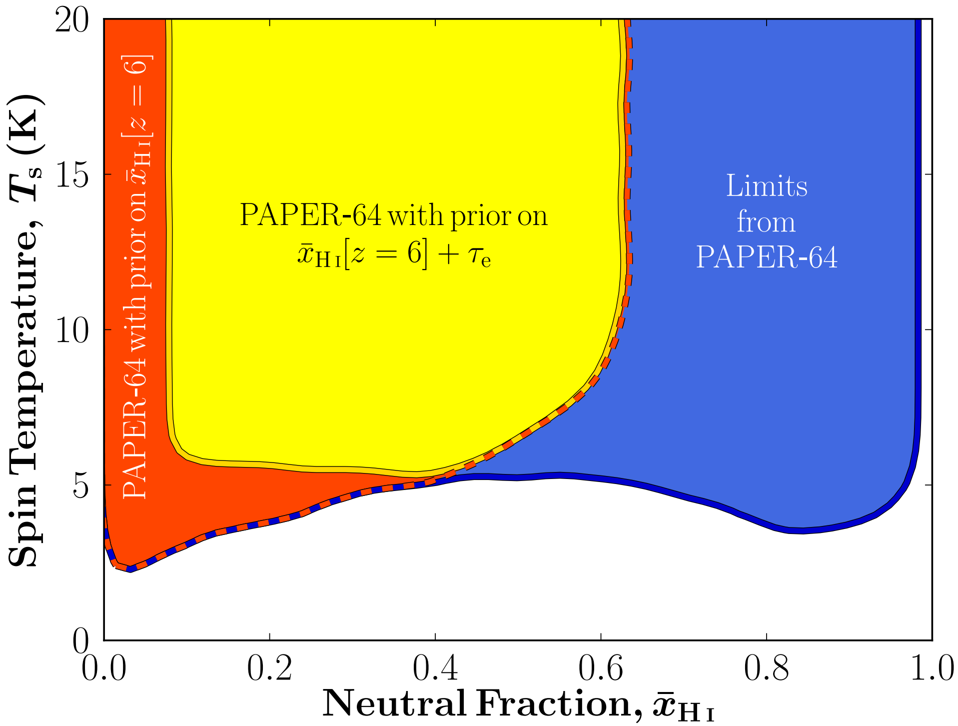
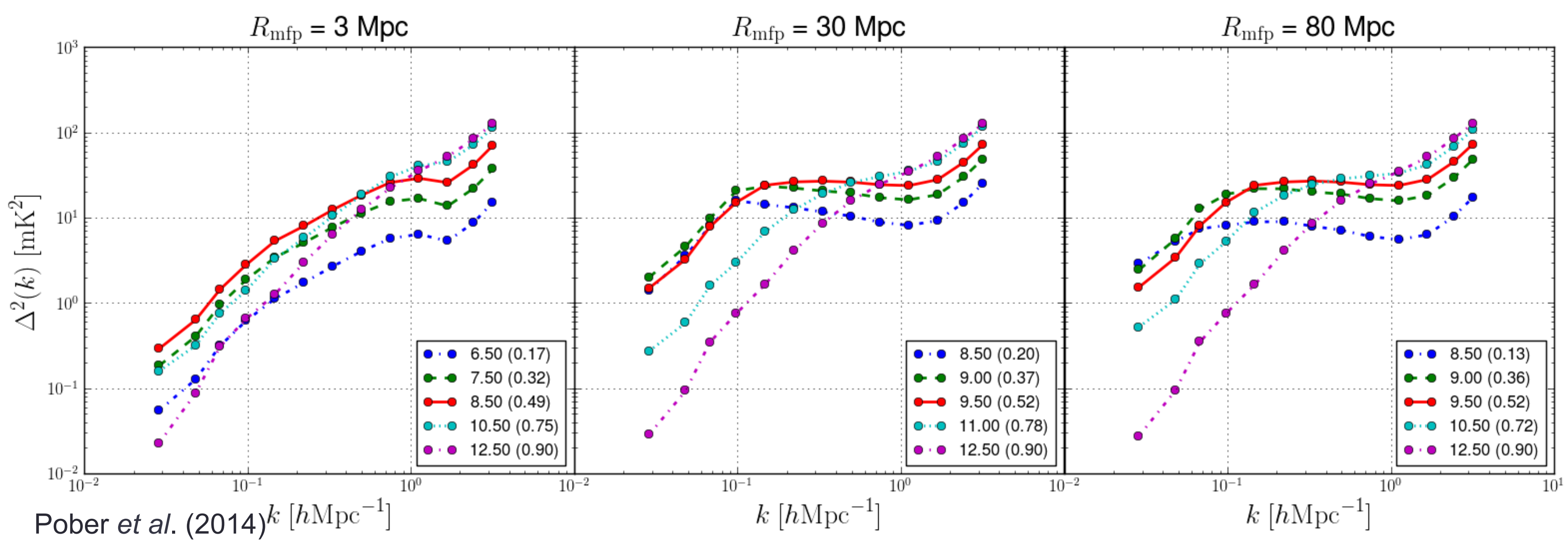


Greig, Mesinger & Pober (2016)

How can we be assured a “first detection” is cosmological?

- Characteristic signatures of cosmological signal (e.g., “knee”, rise and fall vs. z, redshift-space distortions)

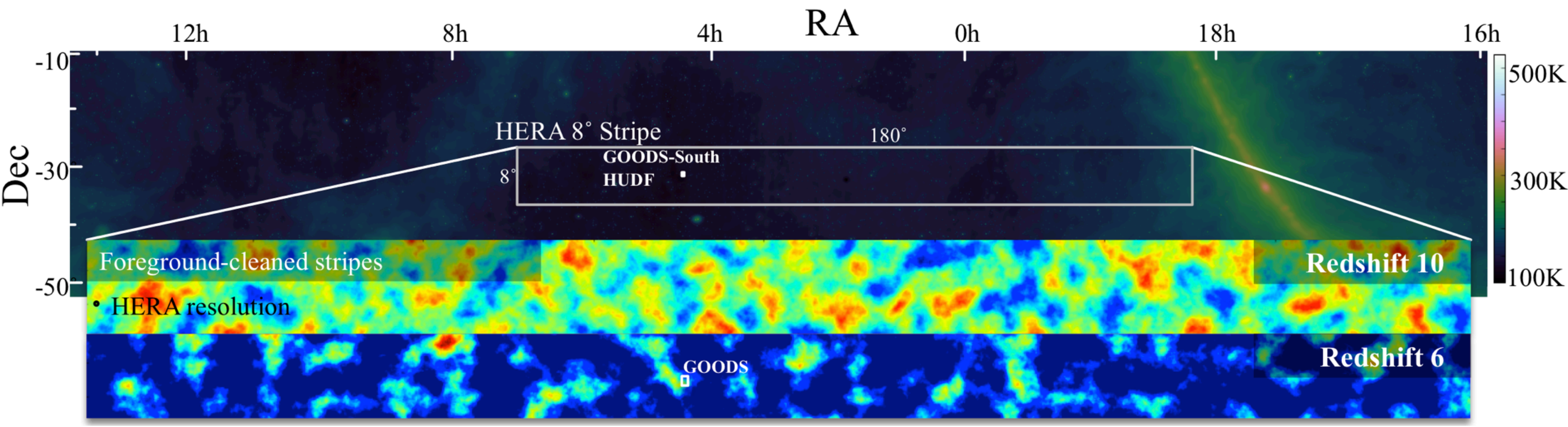


Pober *et al*. (2014)

  - ➢ Not ubiquitous to all models, not necessarily detectable with first generation instruments

How can we be assured a “first detection” is cosmological?

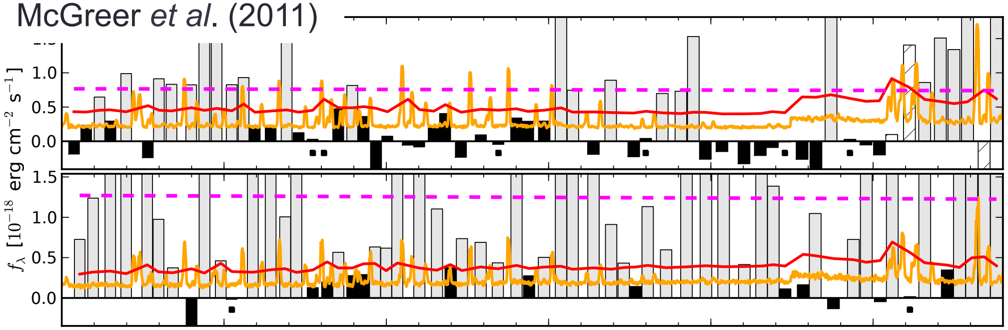
- Cross correlation studies: galaxies/Lyα emitters, FIRB, spectral line intensity mapping

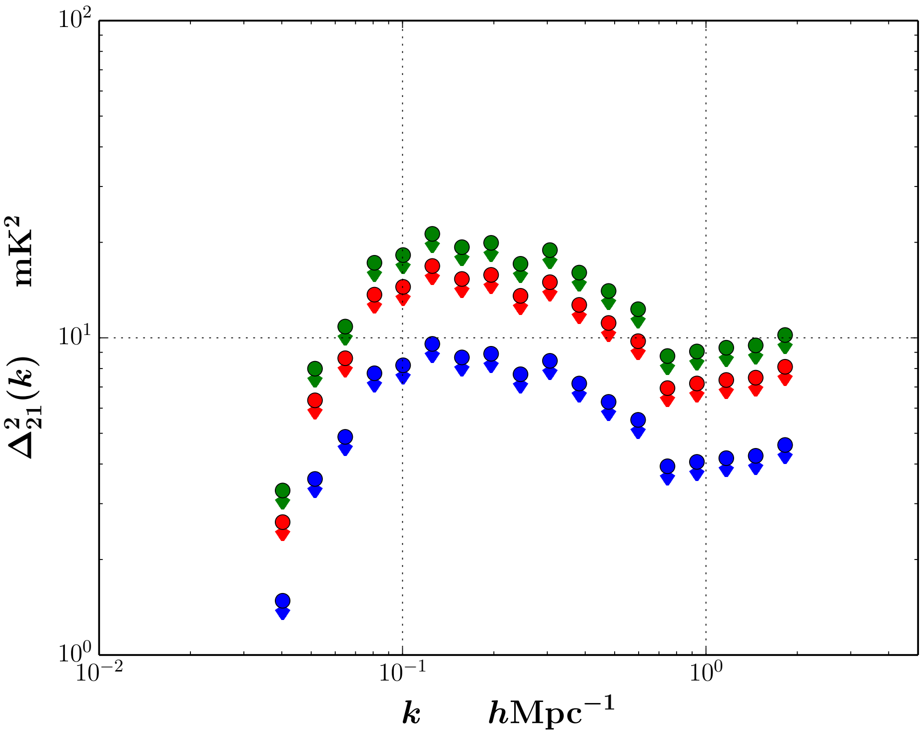


  - Require extremely large survey areas compared to current telescopes or new, dedicated instruments

Holistic analysis with other probes

McGreer *et al*. (2011)



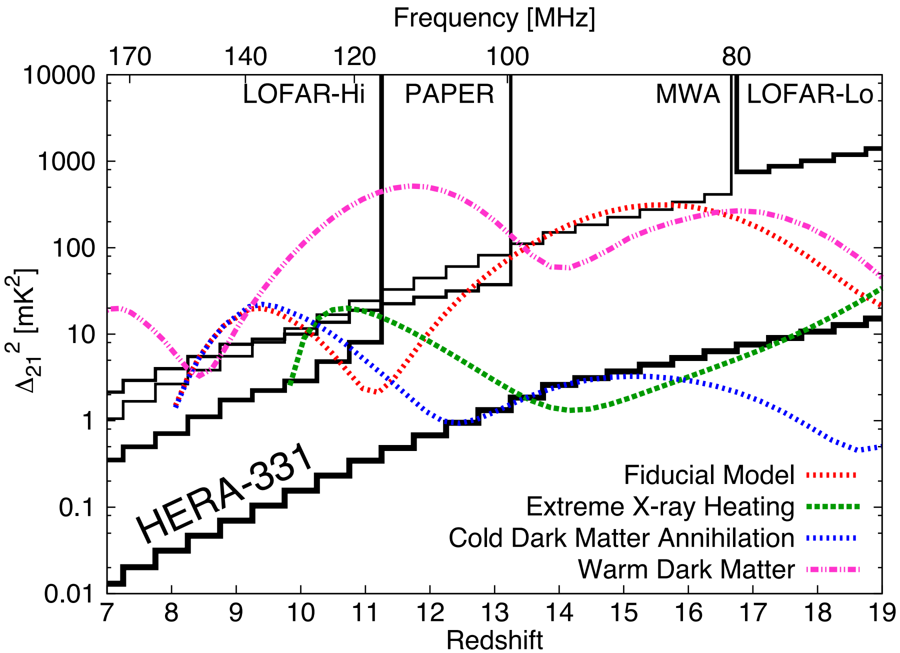


- Quasar absorption spectroscopy can be used to constrain x_{HI} at moderate z
- McGreer et al. (2015) model independent limit (counting dark pixels): $x_{HI} < 0.06 + 0.05$ (1σ) @ z=5.9
- 21CMMC can translate into *quantitative* upper limits on 21 cm signal
  - Null test for end of reionization

Pober, Greig, & Mesinger 2016

Pushing to Lower Frequencies

- Prototype work to improve feed response below 100 MHz
- Recent predictions for “first stars” signal are promising
- Potential to distinguish models of dark matter and sources of heating



Mesinger *et al*. (2013)